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Comparative experimental approach to investigate the thermal behaviour of vertical greened façades of buildings

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Abstract

Greening the building envelope is not a new concept, however it has not been fully approved as an energy saving method for the built environment. Vertical green can provide a cooling potential on the building surface, as plants are functioning as a solar filter and prevent the adsorption of heat radiation of building materials extensively. In this study a comparative thermal analysis of vertical green attached to a façade element is presented. An experimental set up (stationary conditions) has been developed to measure the temperature gradient through a reference cavity wall, in order to quantify the contribution of vegetation to the thermal behaviour of the building envelope. The results show temperature differences between the bare wall and between the different vertical greening systems analysed, up to 1.7 °C for the direct greening system and 8.4°C for the living wall system based on planter boxes after 8 hours of heating for summer conditions, due to the different “material” layers involved. However, the insulation material of the bare wall moderates the prevailing temperature difference between the outside and inside climate chamber, resulting in no temperature difference for the interior climate chamber for summer conditions.

Keywords: vertical greening, green facades, building envelope, climate chamber, thermal behaviour, cooling, insulation

1. Introduction

In dense urban areas the prevalence of paved surfaces (with low albedo) and a lack of natural vegetation are among the major causes of the phenomenon called urban heat island effect: temperature difference between cities and suburban or rural areas is determined by this phenomenon [1], [2]. Introducing vegetation back in our cities is a possibility to alter the microclimate in street canyons [3], [4]. Greened paved surfaces intercept solar radiation and can reduce warming of artificial surfaces as asphalt of concrete, thus reducing the urban heat island phenomenon by two to four degrees Celsius [5], [6]. Outer surfaces of buildings offer a great and unused amount of space for re-introducing vegetation in our cities; green roofs and green façades are possibilities to fulfil this opportunity [7].

Vertical greening systems have a positive influence on the building envelope in terms of thermal performances, as demonstrated by several studies [8], [9]. Hunter et al. [10] show that green façades, like other forms of green infrastructure, are increasingly being considered as a design feature to cool internal building temperatures, reduce building energy consumption and facilitate urban adaptation to a warming climate. In the beginning of the eighties Krusche et al. [11] estimate the thermal transmittance (U) of a 160 mm plant cover at 2.9 $Wm^{-2}K^{-1}$. Also Minke et al. [12] suggested some ideas to reduce the exterior coefficient of heat transfer. By reducing the wind speed along a green façade they suggested that the exterior coefficient of heat transfer of 25.0 $Wm^{-2}K^{-1}$ can be lowered to 7.8 $Wm^{-2}K^{-1}$ which is comparable to the interior coefficient of heat transfer. Holm [13] shows with field measurements and his DEROB computer model the thermal improvement potential of leaf covered walls. A layer of vegetation, as a green façade made of *Hedera helix* can enhance the thermal performances of buildings also during winter season [14]. The authors found the largest savings in energy due to vegetation associated with more extreme weather, such as cold temperatures, strong wind or rain, increasing energy efficiency by 40-50% and enhancing wall surface temperatures by 3°C. Perini et al. [15] show the influence of a green layer on the reduction of the wind velocity along the surface of a building. An extra stagnant air layer in optimal situations can be created inside the foliage, so that when the wind speed outside is the same as inside $R_{exterior}$ can be equalized to $R_{interior,}$ where R is the thermal resistance ($m^2 \cdot K \cdot W^{-1}$). In this way the building's thermal resistance can be increased by 0.09 $m^2 \cdot K \cdot W^{-1}$. Vertical greening systems insulation value can be optimized by covering with high density foliage, creating a stagnant air layer behind the foliage [15], exploiting supporting system materials and their insulation effect and plant species characteristics [14].

Eumorfopoulou et al. [16] reported the temperature cooling potential of plant covered walls in a Mediterranean climate; the effect was up to 10.8 °C. Another recent study by Wong et al. [17] on a free standing wall in Hortpark (Singapore) with vertical greening types shows a maximum reduction of 11.6 °C. The green plant layer will also reduce the amount of UV light that will reach building materials, since by constructing green façades great quantities of solar radiation will be adsorbed for the growth of plants and their biological functions [11]. Since UV light deteriorates the mechanical properties of coatings, paints, plastics, etc. plants will also affect durability aspects of constructions [17]. However, in the case of green façade directly attached, climbing plants may deteriorate the building envelope outer layer, especially in the case of plaster walls [18], [19]

Susorova et al. [20] demonstrate that façade orientation plays an important role as well for cooling capacity due to shadow and evapotranspiration provided by plants. In addition, studies show a potential energy saving for air conditioning that can be obtained with vertical greening systems up to 40-60% in Mediterranean area [3], [21]–[24]

The discussed studies, showing the potential effects of vertical greening systems on the microclimate, are all done under variable environmental conditions.

The present study aims to classify the thermal benefits of green façades or plant covered cladding systems under boundary conditions. The results of this study can be used for giving evidence of the effects of vertical green as an “extra insulation” layer”, to support the decision process for architects, building owners, etc. This “technical/thermal green” strategy of increasing exterior insulation properties of vertical surfaces stimulates upgrading or retrofitting of existing (under-insulated) façades without the added cost of interior or traditional exterior insulation systems. An insulation material mitigates the impact of the created temperature difference between inside and outside [25]. In the research work done by Eumorfopoulou and Aravantinos [26], it was found that a planted roof contributes to the thermal protection of a building but that it cannot replace the thermal insulation layer. From a scientific point of view it is relevant to verify if this effect is also valid for green façades.

A comparison between a bare façade and a plant covered façade is investigated in order to quantify the contribution of vegetation to the thermal behaviour of the building envelope, with three different greening systems applied (a direct green façade and two different living wall systems), during summer and winter seasons.

The experimental study aims at identifying differences between the bare wall and between the different vertical greening systems, due to the different layers involved (a biotic and biotic components).

The experiment presented seeks at analysing the relation between vegetation and the built environment. In particular it is focused on the possible contribution of vertical greening systems in improving the thermal behaviour of the building envelope.

The main objective of the presented study is to measure the temperature gradient through a vertical greened façade element, to quantify the thermal resistance of vertical greening systems and to understand the thermal behaviour in warm (up to 35°C) and cold conditions (down to -5°C).

2. Experimental set up and methodology

This research describes a procedure for comparative measurements of steady-state (stationary condition) heat transfer through a cavity wall with three different vertical greening systems: *Hedera helix* directly to the wall and two living wall systems are based on mineral wool and planter boxes. The bare wall configuration serves as a reference measurement, besides it gives information over the total energy performance of the composite façade when it is covered with vertical green. The living wall system based on planter boxes uses *Lamium galeobdolon, Carex, Alchemilla,* and *Host,* the one based on mineral wool*: Ferns, Geraniums, and Carex.* According to Perini et al. [27], although species have different evaporation capacities, which affect the cooling effect, the major role is played by the supporting system itself. The analysis of these greening systems using different configurations, layers and materials will provide useful information about the influence of the systems' characteristics on thermal performances. The bare wall stratigraphy analysed represents a typical/common European building envelope.

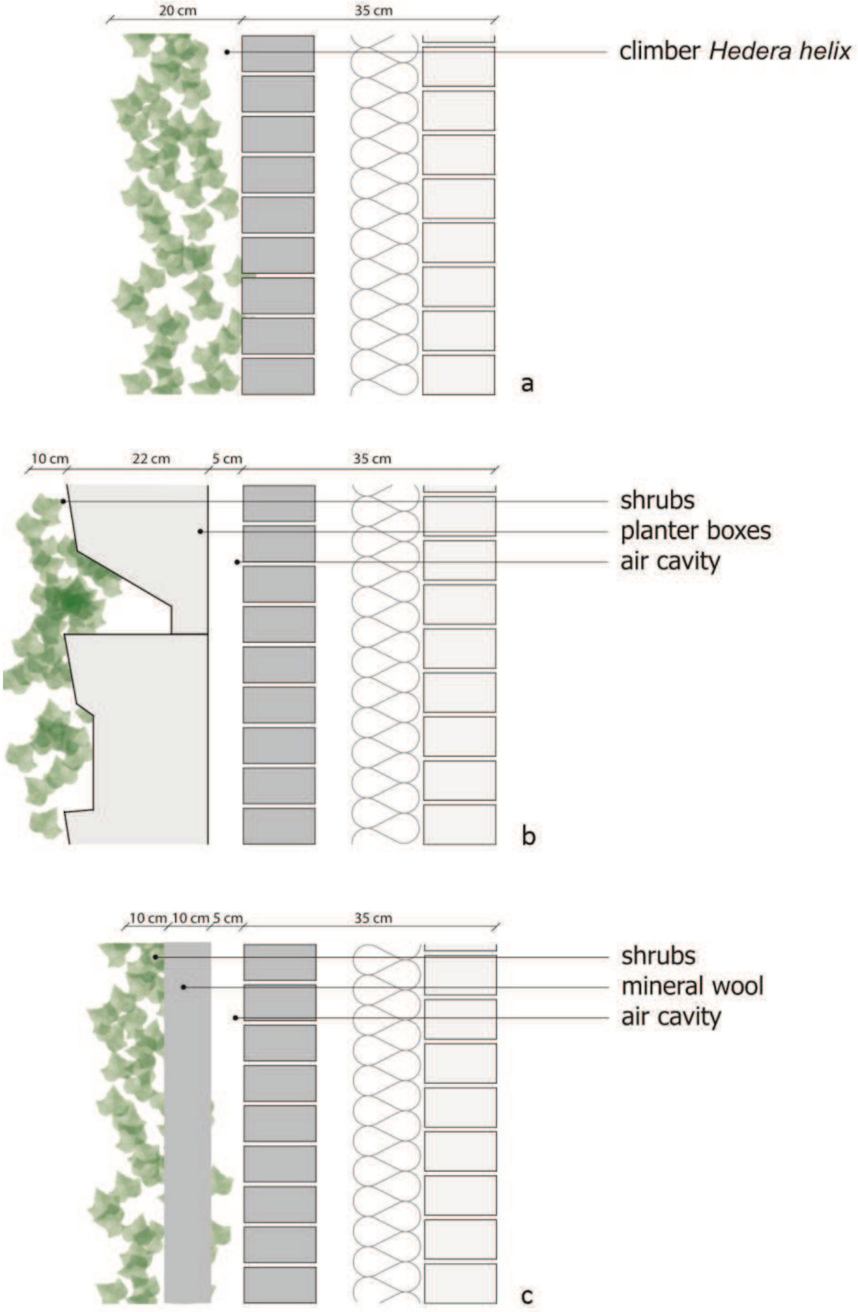

Figure 1 Vertical greening systems analysed in the study: (a) direct green façade, (b) living wall system based on planter boxes, (c) living wall system based on mineral wool.

Figure 2 Cross section of the vertical greening systems analysed in the study (a) direct green façade, (b) living wall system based on planter boxes, (c) living wall system based on mineral wool.

The designed apparatus – called “hot box” – is intended to reproduce different boundary conditions of a specimen between two different environments, in the presented research is chosen for an “indoor” and “outdoor” environment. A digital temperature controller and convective heater as well as infrared radiation bulbs maintain the box temperature as close as possible to environmental outdoor conditions. The total energy input represents the heat transfer through the test system. An automatic data collection system is used in this experiment, so that tests can be conducted over a long period of time (if needed) to assure steady-state conditions and to determine reproducibility of the laboratory measurements.

This study investigates the effects of vertical greening systems in warm (up to 35°C) and cold conditions (down to -5°C). For this reason, representative days are chosen and analysed (according to e.g.[28]). Each system was measured 3 times for summer and winter condition. The summer measurements are conducted over a time span of 8 hours when it is assumed to reach a steady state situation. The winter measurements are conducted over a larger time span of 72 hours to reach a steady state situation.

2.1 Experimental details of the climate chamber

The climate chamber used in this experiment was designed and constructed according to NEN-EN 1934. The standard requires a “hot” chamber on one side of the tested specimen and a heat sink in the form of a “cold” chamber in which environmental conditions are imposed.

The constructed box (the so called “outside and inside” climate chamber) is insulated from its surroundings using 200 mm (two layers overlapped of 100 mm) of expanded polystyrene insulation (EPS) insulation material, with a conductivity of 0.036 W/m.K. The two layers of EPS are glued together and fixed to a plywood face of 18 mm in order to get some stiffness between the panels. In the so called “outside” climate chamber extra insulation material is attached to the EPS in order to minimize heat loss. For this application ISOBOOSTER-T1 sheets of 240 mm thickness are used with a *U* - value of 0.42 $W/m^2{\cdot}K$. The outside and inside climate chambers have the same dimensions and are as follows (figures 3 and 4):

- length L = 1.10 m
- width w = 1.40 m
- height H = 1.40 m

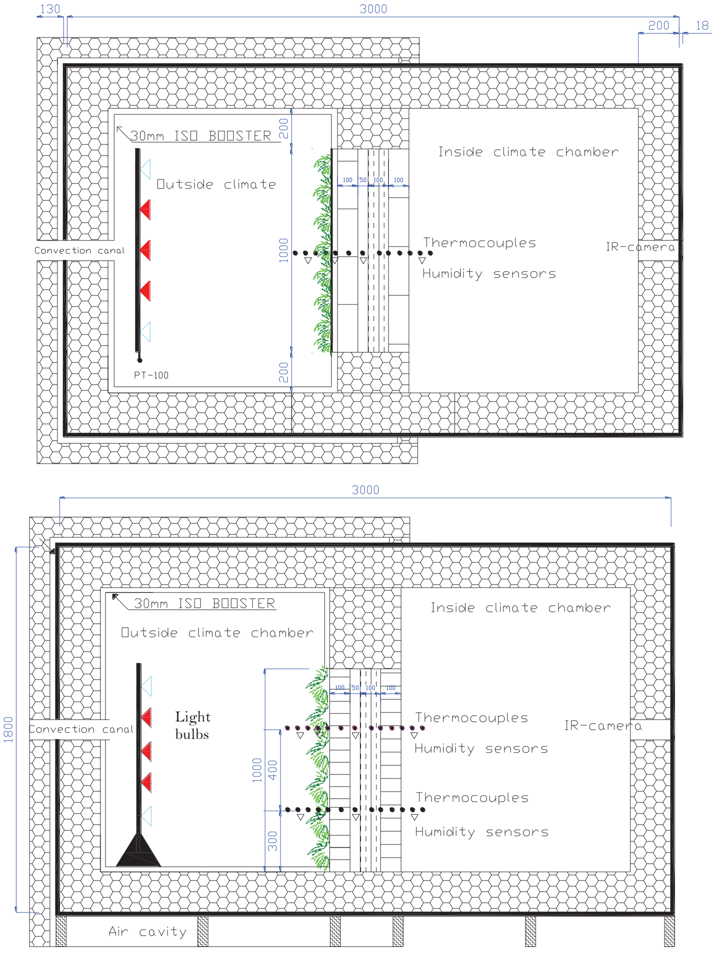

Figure 3 top view and cross section view of the designed box and the positions of the thermocouples used; dimensions in mm.

In the middle of the box a cavity wall is constructed as reference material and to test vertical greening systems placed in front of it (figure 4). The cavity wall also directly forms a sample holder for vertical green cladding systems. For the living wall systems an air cavity is created between living wall panel and the façade (figure 1).

Figure 4 side and front view of the constructed cavity wall used for the experiments.

In this way the box is divided into two chambers: an “outside” climate chamber and an “inside” climate chamber as it is mentioned in the text. In order to minimize the heat loss through the walls of the “outside” climate chamber, an extra insulation layer of 100 mm EPS with an air cavity of 30 mm is constructed at the outside of the box (only around the outside climate chamber). This extra layer serves as a guard by keeping the temperature of the air cavity the same as temperature in the “outside” climate chamber. The guard section ensures that the lateral heat flow rate from the outside chamber is nearly zero to the guard section. The relative humidity in the climate chamber was measured by Honeywell hygrometers with a thermoset polymer capasive sensing element during the experiments to exclude the influence of evapotranspiration of the different green systems. The relative humidity in the “outside” climate chamber was brought to 85% with an electric Honeywell ultrasonic air humidifier before the measurement was started.
The temperature of the guard section (extra air cavity) is controlled with a PT100 in combination with an ENDA ET1411 digital thermostat temperature controller (connected to a solid state relay). The box tightness (thermal leakage) inside and outside the box was determined by the use of an infrared camera (FLIR A320).

Temperature measurements were made using thermocouples and PT100 sensors. Amount and position of the thermocouples is given in table 1 and schematically presented in figure 3. The data is collected and recorded on a data logger with a frequency of acquisition of 60 scans per hour. The total system is controlled by a personal computer. In order to study the effect of convection (warm air) and radiation (sunshine) on the heat transfer trough a greened wall both are tested separately.

Control system convection and radiation

The convection heating system in the climate chambers (inside/outside) consists of a hot gun in an insulated enclosure. The maximum power output of the hot gun is 1500 Watt. The temperature of the outside climate chamber is also controlled with a PT100 in combination with an ENDA ET1411 digital thermostat temperature controller. The radiation power system in the outside climate chamber consists of nine PAR38 light bulbs placed in front of the specimen which are used to supply radiation energy, during summer measurements (Figure 3), which must simulate the radiation. Three PAR30 light bulbs were used during summer and winter measurements to serve as daylight and to ensure that metabolism and photosynthesis processes could continue during the measurements.

Data acquisition

For the thermal data acquisition four calibrated “Advantech 4781” USB modules are used to read the thermocouples. The data acquisition for the humidity sensors is done by a multifunctional DAQ NI USB-6211 module.

Thermocouple measurements

All used thermocouples are of type T (Cu-Ni) with a diameter of 0.25 mm. Two PT100 are used to measure the temperature in the outside climate chamber and in the guard section. Near the PT100 a thermocouple was placed to verify the temperature in the outside climate chamber. Each thermocouple measurement consists of two measurements on the same x-axis but on a different height (y-axis) (figure 3, shown by the dotted lines).

The temperature inside the canopy of the tested vertical greening systems is measured by placing thermocouples on the backside of the leaves with thin transparent tape.

Specimen/sample mounting

The reference cavity wall consists of an inner wall of 100 mm thickness (limestone), mineral insulation material of 100 mm thickness (Rockwool), cavity of 50 mm thickness and an outer wall of 100 mm thickness (brick), (figure 5).

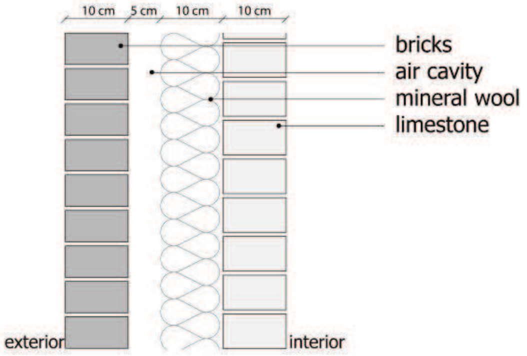

Figure 5 cross section of the reference cavity wall as used for the experiment.

2.2 Theoretical calculations - thermal transfer coefficient

For the thermal transfer coefficient the symbol *U* is used. The coefficient ($Wm^{-2} K^{-1}$) expresses the quantity of energy (W) passing through a material per area (m^2) and per temperature difference (K) between the two sides of the material. From thermal equilibrium theory it follows that:

$$U = \frac{Q}{A\left(T_i - T_e\right)} = 1/R \qquad (1)$$

With *Q* the energy required for heating, *A* the area of the specimen, T_i the temperature of the inside chamber and T_e the temperature of the outside chamber. The formula can be used under the conditions that the heat transfer through the specimen is stable and that there are no heat losses thought the wall of the heating chamber. The extra insulation layer with heated cavity (same temperature as inside the outside chamber) ensures that there is no exchange of heat out of the chamber. The heat loss therefore can be neglected.

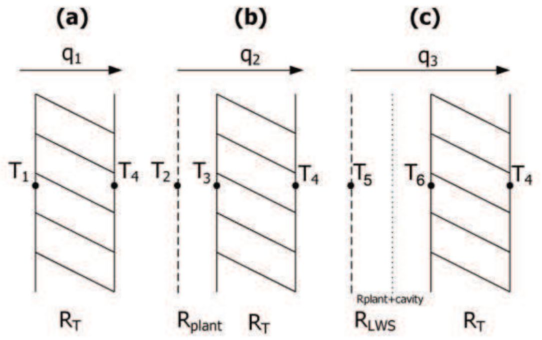

Figure 6 Variables used for calculating the heat flow through a bare façade (a), directly greened façade (b) and a façade covered with a LWS panel (c). The dotted line represents the air cavity between plants and wall and the dashed line the plants.

For steady state conditions, the rate of heat flow (q) per unit area through the building's fabric with an R-value, an indoor surface temperature (T_4) and an outdoor surface temperature (T_1) is given by equation (2).

$$q_1 = \frac{(T_1 - T_4)}{R_T} \qquad (\mathrm{W\ m^{-2}}) \qquad (2)$$

Where T_1 (K) is the external surface temperature, T_4 (K) is the internal surface temperature, R_T ($\mathrm{m^2 \cdot K \cdot W^{-1}}$) is the thermal resistance of the wall.

As for the direct greened façade can be found:

$$q_2 = \frac{(T_2 - T_4)}{R_{plant} + R_T} = \frac{(T_2 - T_3)}{R_{plant}} + \frac{(T_3 - T_4)}{R_T} \quad (\mathrm{W\ m^{-2}}) \qquad (3)$$

Where q is the heat flow, T_2 (K) is the surface temperature of plants, T_3 (K) is the surface temperature below plants and R_{plant} ($\mathrm{m^2 \cdot K \cdot W^{-1}}$) the thermal resistance of the plant species. For a façade covered with LWS panels can be found:

$$q_3 = \frac{(T_5 - T_4)}{R_{LWS} + R_T} = \frac{(T_5 - T_6)}{R_{LWS}} + \frac{(T_6 - T_4)}{R_T} \qquad (\mathrm{W\ m^{-2}}) \qquad (4)$$

Where T_5 (K) is the surface temperature of the living wall system, T_6 (K) is the surface temperature below LWS and R_{LWS} ($\mathrm{m^2 \cdot K \cdot W^{-1}}$) the thermal resistance of the LWS.

Via expression (2) one can derive the thermal resistance of the plant layer for a direct greened façade (eq. 3). The same can be found for the thermal resistance of a façade covered with a LWS concept (eq.4):

$$R_{PLANT} = R_T \frac{(T_2 - T_3)}{(T_3 - T_4)} \qquad (\mathrm{m^2 \cdot K \cdot W^{-1}}) \qquad (5)$$

$$R_{LWS} = R_T \frac{(T_5 - T_6)}{(T_6 - T_4)} \qquad (\mathrm{m^2 \cdot K \cdot W^{-1}}) \qquad (6)$$

In order to calculate the overall thermal resistance of the reference cavity wall and the vertical green systems analysed the material properties are used as given by the product information sheets of the used materials in this experiment (Table 2). Besides it was used to compare the theoretical calculations with the retrieved measuring data from the experimental set up. The theoretical temperature line is for this purpose as well plotted in figures 7-12. The question mark in table 2 represents the experimentally value to determined for thermal resistance of a vertical green system in the presented research.

Table 2 cavity wall + vertical greening systems layers and related thermal resistance and conductivity.

Nr.	Layers of the construction	Thickness d *[m]*	Thermal conductivity *λ* *[W/(m·K)]*	Thermal resistance construction $R_c = d/\lambda$ *[(m²·K)/W]*
0	***Vegetation layer***	**0.1-0.2**		**?**
1	*external surface resistance*			0.04
2	masonry (clay)	0.1	1.00	0.10
3	Cavity	0.05		0.17
4	insulation material (mineral wool)	0.1	0.035	2.85
5	masonry (lime stone)	0.1	1.00	0.10
6	*internal surface resistance*			0.013
Total		0.45-0.55		**3.27 + ?**

3. Results and discussion

3.1 Direct façade greening

For the direct greening principle it is found that for the summer condition the average temperature of the wall surface ($T_{\text{ext wall surface}}$) is lower compared to the bare wall. The difference of temperature is reaching 1.7°C after 8 hours of heating. The insulation material inside the bare wall moderates the prevailing temperature difference between the outside and inside climate chamber, resulting in no temperature difference for the inside climate chamber (figure 7). The winter measurement after 72 hours shows that the wall surface covered directly with *Hedera helix* is warmer compared to the bare wall, with a temperature difference of 1.7°C. The air temperature of the inside climate chamber is lowered with 0.7°C in the case of the bare wall, which means that the vegetation layer slows down the rate of heat flow through the façade, resulting in an improved *R-value* of the system compared to the bare façade (figure 8).

3.2. Living wall system based on planter boxes

For the planter boxes system (LWS), it was found that for the summer condition the average temperature of the wall surface is lower compared to the bare wall, with a temperature difference reaching 8.4°C after 8 hours of heating (figure 9). This is a substantial difference with the direct greening system. Also for the living wall system based on planter boxes it was noticed that the insulation material inside the bare wall moderate the prevailing temperature difference between the outside and inside climate chamber, resulting in no temperature difference for the interior climate chamber. It is noteworthy to mention that the temperature difference between the air of the exterior chamber and the temperature of the extra created air cavity between LWS and façade is 8.6°C. It was noticed that the humidity inside the exterior climate chamber lays between 85% and 100% for the measurement; this is probably related to the moisture content of the substrates used for the living wall systems.

The winter measurement shows after 72 hours a temperature difference between the surface of the bare wall and the wall covered with planter boxes of 10.6°C, with a temperature difference between the exterior air temperature and the extra created cavity of 5.5°C. The interior air temperature difference after the measurement came up 2.1°C and thus resulting in an improved *R-value* of the system compared to the bare façade (figure 10).

<u>3,3. Living wall system based on mineral wool</u>

For the living wall system based on mineral wool (LWS), it was found that for the summer condition the average temperature of the wall surface is lower compared to the bare wall, with a temperature difference reaching 5.9°C after 8 hours of heating (figure 11). The air temperature difference between the exterior chamber and the air temperature of the extra created air cavity between LWS and façade was 5.9°C.

The winter measurement show a temperature difference after 72 hours between the surface of the bare wall and the wall covered with planter boxes of 10.6°C, with a temperature difference between the exterior air temperature and the extra created cavity of 4.6°C. The interior chamber air temperature difference after 72 hours came up 2.1°C and thus resulting also in an improved *R-value* of the system compared to the bare façade (figure 12).

Table 3. Summer season, temperatures recorded for 8 hours based on steady state situation.

Systems analysed	**measuring points summer temperature (°C)**				
	T_{ext}	$T_{foliage}$	$T_{ext.\ wall\ surface}$	$T_{int.\ surface\ (outside)}$	$T_{int.}$
bare wall	*34.8*	--	*T_1; 32.6*	*T_4; 24.3*	*24.1*
(a) direct green façade	34.1	**T_2**; 31.4	**T_3**; 31.0	**T_4**; 23.9	24.0
(b) living wall system based on planter boxes	31.8	**T_5**; 29.4	**T_6**; 24.2	**T_4**; 23.4	23.1
(c) living wall system based on mineral wool	34.8	**T_5**; 30.4	**T_6**; 26.8	**T_4**; 24.7	24.4

Table 4, Winter season, temperatures recorded for 72 hours based on steady state situation

Systems analysed	**measuring points winter temperature (°C)**				
	T_{ext}	$T_{foliage}$	$T_{ext.\ wall\ surface}$	$T_{int.\ surface\ (outside)}$	$T_{int.}$
bare wall	*-7.6*	--	*T_1; -6.6*	*T_4; 17.7*	*17.9*
(a) direct green façade	-6.2	**T_2**; -6.4	**T_3**; -5.0	**T_4**; 19.2	19.9
(b) living wall system based on planter boxes	-1.2	**T_5**; -2.1	**T_6**; 4.0	**T_4**; 20.0	20.1
(c) living wall system	-2.1	**T_5**; -3.0	**T_6**; 4.0	**T_4**; 20.1	20.0

based on mineral wool					

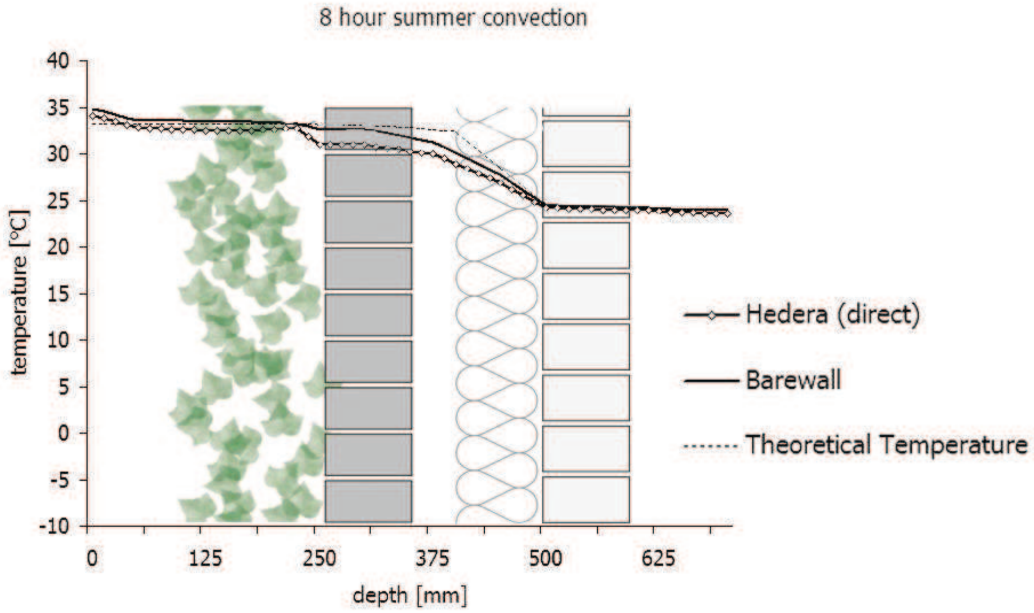

Figure 7 direct green façade – 8 hours summer convection

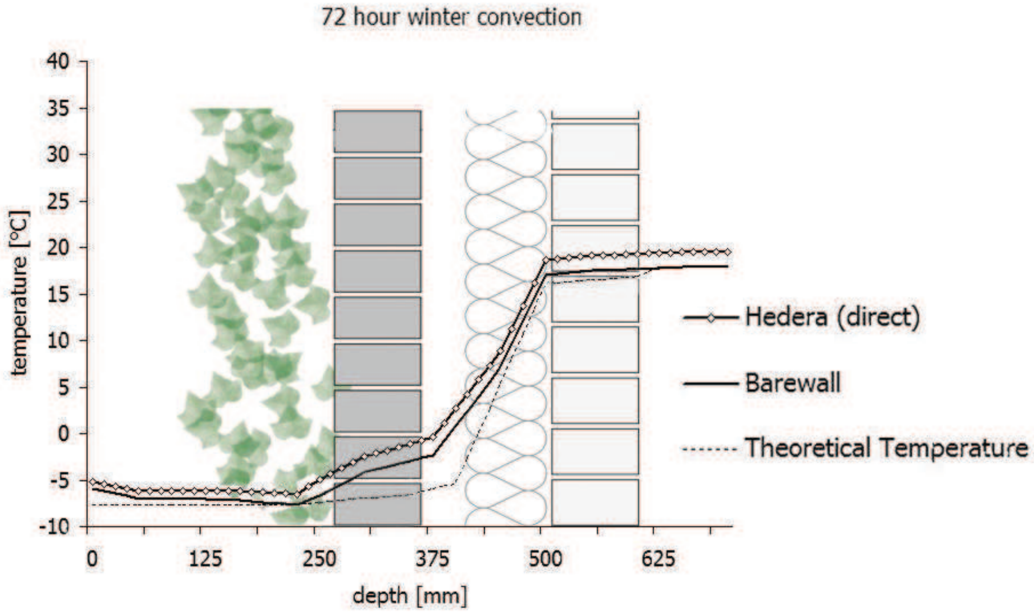

Figure 8 direct green façade – 72 hours winter convection

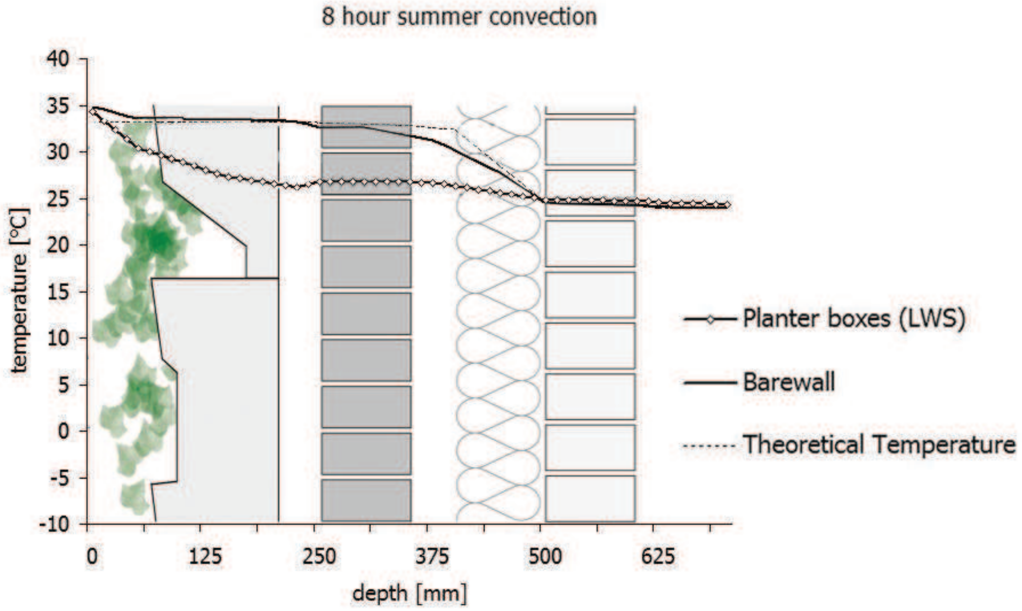

Figure 9 LWS based on planter boxes – 8 hours summer convection

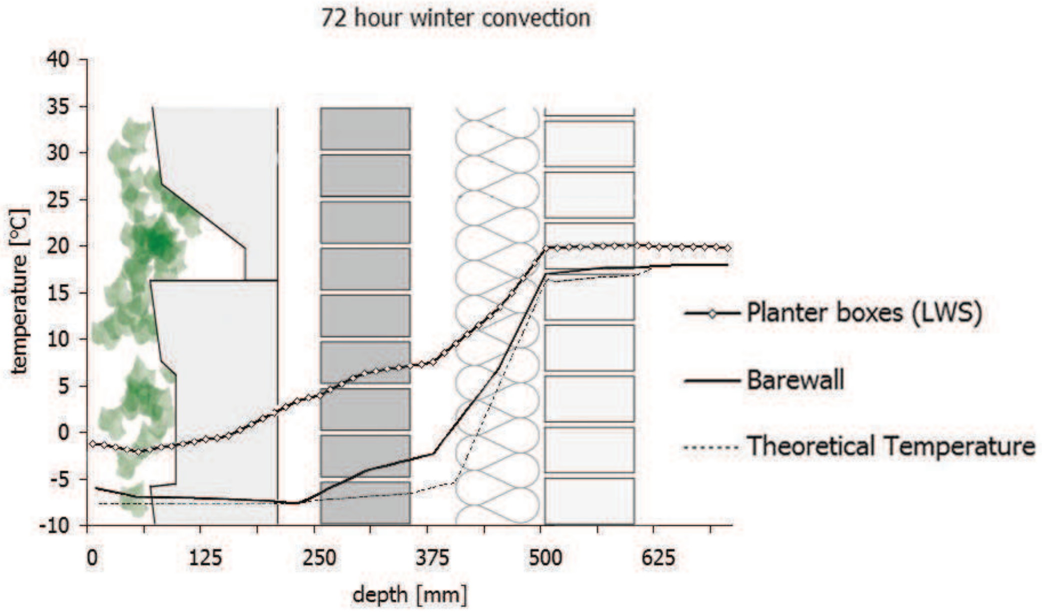

Figure 10 LWS based on planter boxes – 72 hours winter convection

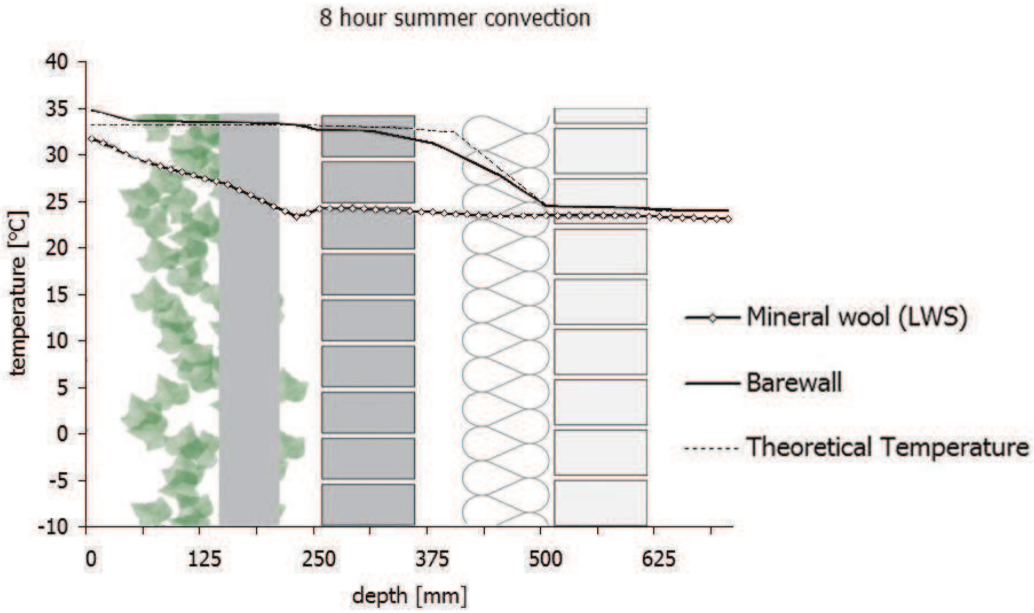

Figure 11 LWS based on mineral wool – 8 hours summer convection

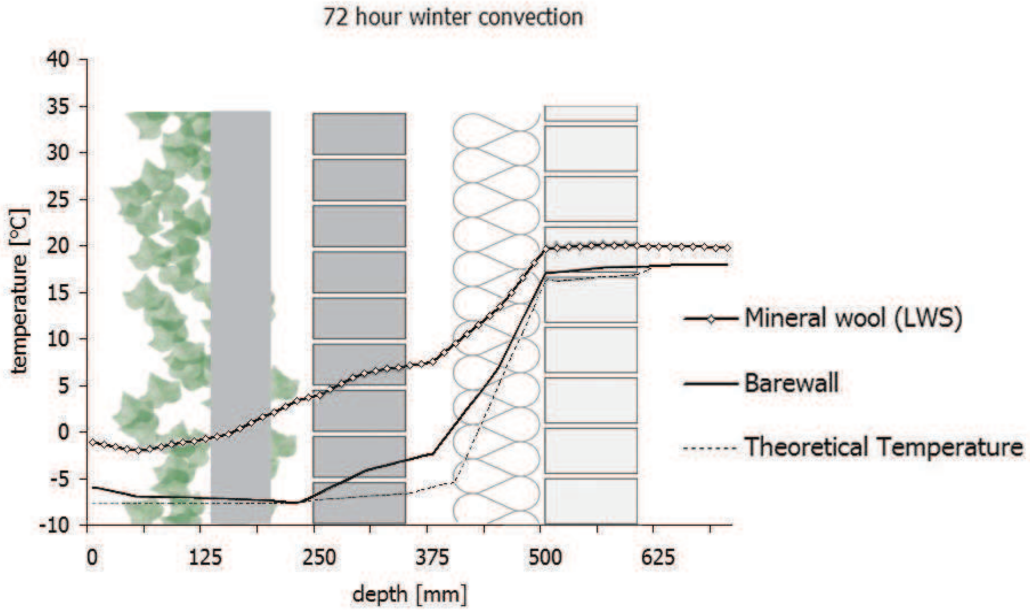

Figure 12 LWS based on mineral wool – 72 hours winter convection

3.4 Calculation of thermal resistances and critical analysis of the obtained data

The conducted experiment allows estimating the thermal resistance of the vertical greening systems, according to paragraph 2.2. The calculation of equivalent R-values is based on the data collected in the experimental climate chamber, in particular on the measured interior and exterior surface temperatures, both for a summer and winter situation (Tables 5-6). For steady state conditions, the rate of heat flow per unit area through the direct greened façade can be estimated according to equations 3 and 5. For the living wall concepts equations 4 and 6 are used.

Table 5 Estimated R-values for the greening systems tested under summer condition; assuming a steady state situation after 8 hours of heating. The values regarding the living wall systems must be considered as not reliable due to the unexpected high value(s).

Summarized thermal resistances summer measurement	
Vertical greening systems	*R-value* ($m^2 \cdot K \cdot W^{-1}$)
Bare wall	3.43
Hedera helix direct	0.66
LWS based on planter boxes	*12.81*
LWS based on mineral wool	*33.15*

Table 6 Estimated R-values for the greening systems tested under winter condition; assuming a steady state situation after 72 hours of cooling.

Summarized thermal resistances winter measurement	
Vertical greening systems	*R-value* ($m^2 \cdot K \cdot W^{-1}$)
Bare wall	3.42
Hedera helix direct	0.18
LWS based on planter boxes	1.30
LWS based on mineral wool	1.10

The R-values values calculated for the summer measurement (Table 5) are extremely high. This is probably related to insufficient measuring time (8 hours) to reach a steady state situation for the heat flow through the vertical greening systems, in particular for the living wall systems analysed, due to the high temperature differences between the several layers (vegetation, materials, air, etc.) involved. The temperature gradient ΔT_{lws} (difference between T_1 and T_2) has a high influence on the outcome of the equation used (eq. 6). The larger the temperature drop over the living wall system, the higher the R_{LWS} value will be. In the case of the summer measurements after 8 hours heating, high temperature gradient (T_1-T_3 up to 10°C) over the living wall systems was found as earlier described (see also figures 10 and 12), whereas the temperature gradient over the bare wall (T_3-T_4) appeared to be 1.5°C as a maximum. Noteworthy to mention is the striking temperature drop found for the LWS systems under summer conditions between the supporting material and substrate and façade (figures 10 and 12). The reason for this could be because of the evaporative cooling capacity of the composite system, however further research is needed to really understand this mechanism.

Worth mentioning; the real effect of the moisture content (evapotranspiration; the contribution of vegetation and substrate) on the heat transfer mechanism is inside a closed and sealed environment should be further investigated. In fact, also the evaporation and the water (vapour) trapped inside the chambers plays a role. It is likely that this mechanism causes the high temperature differences found for the summer measurement. Building materials (abiotic) are tested via the same principle (steady state) according to the standard NEN-EN 1934, the difference with the executed experiment is the introduction of a (unknown) biological factor. In practice the (exterior climate chamber) humidity levels are affected due to ventilation by wind. Interior humidity levels are mostly influenced by the use of a building (human activity, cooking, etc.).

R-values deriving from winter measurement, presented in table 6, are lower compared to the ones derived from summer measurements. This is related to the measuring time of 72 hours which tends to be really steady state. Another important aspect is the evaporative character of the vertical greening systems under colder temperatures (frost) which is less compared to the summer measurement were the plants (+substrate) are constantly (evapo)transpirating to fulfil their biological functions (metabolism). Again it is observed that the greening systems positively influence the temperature development through the façade. This still indicates that the thermal resistance of the construction is improved by adding a green layer.

Conclusion

The present research allows studying the thermal behaviour during summer and winter seasons of different vertical greening systems under boundary conditions. From the summer measurements a considerable effect in reducing the temperature development in the exterior masonry by applying vertical greening systems can be noticed, in particular for the living wall systems analysed. This means that less accumulation will occur in a greened façade, resulting in less heat radiation at night. Such effect results in energy saving for air conditioning and also in a possible reduction of urban heat island effect. It can also be noticed that the greening systems influence positively the temperature development through the façade, resulting in an improvement of the thermal resistance of the construction.

The results obtained show that the experimental set-up (climate chamber “hotbox”) acts wherefore it was designed, as from a building physics point of view positive temperature differences were found between the bare wall and the different vertical greening systems attached to the same bare wall configuration.

The main conclusions that can be drawn from the presented results are the following:

- For all the cases analysed it was noticed that the insulation material inside the bare wall moderates the prevailing temperature difference between the outside and inside climate chamber, resulting in no temperature difference for the interior climate chamber for summer conditions in this comparative study. However vertical greening system reduce outdoor temperature resulting in urban heat island mitigation.
- Temperature differences can be found between the bare wall and vertical greening systems that were attached to the same bare wall.
- The direct façade greening intercepts the solar radiation as shown by the temperature difference of 1.7°C after 8 hours of heating for summer conditions; for winter conditions warmer temperatures are found due to the presence of *Hedera helix,* which means that the vegetation layer slows down the rate of heat flow through the façade, resulting in an improved *R-value* of the system compared to the initial bare supporting wall.
- The results related to the living wall system based on planter boxes show a temperature difference reaching 8.4°C after 8 hours of heating compared to the bare wall; for the winter measurement the interior air temperature difference after the measurement came up 2.1°C and thus resulting in an improved *R-value* of the system compared to the initial bare supporting wall.
- The living wall system based on mineral wool is the most effective with regard to summer cooling with a temperature difference reaching 5.8°C after 8 hours of heating compared to the bare wall. For the winter measurements a similar trend compared to the living wall system based on planter boxes was noticed (i.e. the interior chamber air temperature difference after 72 hours came up 2.1°C), resulting in an improved *R-value* of the system compared to the initial bare supporting wall.

This research gives insight in the positive influence of green systems on the thermal behaviour of buildings. Starting from the measurements, an estimation of R-values is provided. In order to obtain more realistic results regarding the *R-value* of greening systems, reaching a steady state situation (with a measuring form more than 8 hours) and improving of the climate chamber is needed. In fact, enlarging the volume of the exterior chamber (i.e. where the greenery is placed) could lower the influence of evaporation. Additional research is required for an accurate thermal resistance calculation.

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