Vertical greening systems and the effect on air flow and temperature on the building envelope

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Abstract

The use of horizontal and vertical greening has an important impact on the thermal performance of buildings and on the effect of the urban environment as well, both in summer and winter. Plants are functioning as a solar filter and prevent the adsorption of heat radiation of building materials extensively. Applying greening is not a new concept; however it has not been approved as an energy saving method for the built environment. Vertical greening can provide a cooling potential on the building surface, which is very important during summer periods in warmer climates. In colder climates evergreen species create an external insulation layer and contribute to energy savings and loss of heat. In this study an analysis of the effect on air flow and (air and surface) temperature of vertical greening systems on the buildings are presented. An experimental approach was set up to measure the temperature (air and surface) and the air flow near and on different types of green façades and a living wall system to evaluate the influence of wind velocity and its effect on the thermal resistance. A comparison between measurements on a bare façade and a plant covered façade has been taken, in the beginning of autumn, to understand the contribution of vegetation to the thermal behaviour of the building envelope.

1. Introduction

The integration of vegetation on buildings, through green roofs or vertical greening, allows obtaining a significant improvement of the building's efficiency, ecological and environmental benefits. The benefits gained thanks to the use of vegetation are the subject of studies and researches starting from the seventies [3]. During this period the first projects which revolved around nature and the environment emerged such as the work of the American architect James Wines who is associated with the SITE group, Emilio Ambasz, Rudolf Doernach, and Oswald Mathias Ungers.

Green façades and living wall systems (LWS) offer numerous ecological and environmental benefits, can have a positive influence on the comfort and well being in and around the building, besides social and aesthetic value [3]. The ecological and environmental benefits of vertical greening systems, as for green roofs, concern the reduction of the heat island effect in urban areas, the air quality improvement [10] and energy savings. In fact both the growing medium and the plants themselves provide insulation and shade which can reduce, especially in Mediterranean area, energy for cooling [13].

Starting from climbing plants planted at the base of building façades, diffuse in traditional architecture since 2000 years ago, there are now several different ways for vertical greening. The many systems available on the market can be classified into façade greening and living walls systems [7].

Green façades are based on the use of climbers (evergreen or deciduous) attached themselves directly to the building surface (as in traditional architecture), or supported by steel cables or trellis. Living wall systems, which are also known as green walls and vertical gardens, are constructed from modular panels, each of which contains its own soil or other growing medium (soil, felt, perlite, etc) based on hydroponic culture, using balanced nutrient solutions to provide all or part the plant's food and water requirements [4].

Living wall systems and green façades have different characteristics that can have influence on some of the benefits like cooling and insulating properties. This comes, among other things, due to the thickness of the foliage (creating a stagnant air layer and shading the façade), water content, material properties and possible air cavities between the different layers. The role of stagnant air layers is to slow down the rate of heat transfer between the inside and outside of a building.
By constructing green façades and green roofs great quantities of solar radiation will be absorbed for the growth of plants and their biological functions. Significant amounts of radiation are used for photosynthesis, transpiration, evaporation and respiration [8]. A part of (5–30%) the remaining solar radiation is passing through the leaves and affects the internal climate of buildings when it passes the façade or roof. Especially in dense and paved urban areas, the impact of evapotranspiration and shading of plants can significantly reduce the amount of heat that would be re-radiated by façades and other hard surfaces. At the building level, as a consequence, every decrease in the internal air temperature of 0.5 °C can reduce the electricity use for air conditioning up to 8% [4].

Covering façades with leaves on outside walls, also known as green façades or vertical greening, is discussed in many studies. Field measurements on a plant covered wall and a bare wall by Bartfelder and Köhler [1,2] shows a temperature reduction at the green façade in a range of 2–6 °C compared with the bare wall. Also Rath and Kießl [12] measured differences in the temperature gradient across a green covered wall. The corresponding factor in both researches is that at 1 m in front of the vegetation layer no gradient across a green covered wall. Green façades, however, change the wind velocity on the exterior surface for calculating the heat transfer coefficient. For interior surfaces the standardisation [9] applies 0.2 m/s along the wall surface. Green façades, however, change the wind velocity on the underlying exterior construction material. According to literature it is claimed that leaves (foliage) of plants create an almost stagnant layer of air or reduce the wind strength proportional [5,6], values however of these effects are missing or hardly known in literature.

In this study three common systems for vertical greening of buildings situated in Delft, Rotterdam and Benthuizen (The Netherlands) are considered and analyzed (Fig. 1):

1. Direct façade greening system
2. An indirect façade greening system
3. A living wall system based on planter boxes filled with potting soil

1.1. Aim of the study and research questions

There are claims in literature [8,11] about the insulation properties of greening façades due to a reduction of the wind speed which can cause a possible stagnant air layer or an “extra” air cavity; however these effects are not quantified yet. Therefore the aim of this study is to quantify the above described possible effects. Beside this the objective of the quantification is to evaluate the potential energy savings (energy needed for heating and cooling) with different vertical greening systems due to the increase of the insulation properties of buildings.

Since the aim of this research is to measure the possible reduction of the wind velocity and (air and surface) temperature by different green concepts (direct, indirect and LWS), the following research questions have been formulated:

- Is there a difference in wind speed reduction between different greening systems?
- Is there a difference between air temperature in front of a bare façade compared with a greened one and between the surface temperatures of the bare and greened façades?

2. Materials and methods

The chosen greening systems for this research are based on different characteristics such as materials used, plant type and configuration. Due to the characteristics of each investigated greening system it is hypothesized that there is a difference on the microclimate (air-, surface temperature and wind speed) around and in, behind the green walls. The locations of the three façades investigated are all in the Netherlands (province Zuid-Holland) and are not further away than approximately 20 km from each other (Fig. 1).

The direct façade greening (Fig. 2a), situated in Delft on a 1920 building, consists of a well grown evergreen climber Hedera helix, attached directly to the building surface and planted at the base of the greened façade. The second system analyzed in this study is based on an indirect façade greener (Fig. 2b) situated on the façade of 280 m² of a residential building from the seventies in Rotterdam. This system is constituted by aluminium pots, filled with soil, placed at several heights and connected to steel frames, acting as support for evergreen climbing plants (H. helix, Vitis, Clematis, Jasmine and Pyracantha) with a computer-controlled system for water and nutrients. The third investigated greened façade, a living wall system (Fig. 2c), located in Benthuizen, is based on plastic modules (HDPE), filled with potting soil and planted with several evergreen species (no climbers), with a computer-controlled system for water, nutrients and drainage.

All of the air-, surface temperature and wind measurements are done from September till end of October 2010, during days without rain or extreme high wind speeds (above 10 m/s). Measurements have been done between 12:00 and 15:00 h.

The period have been chosen for the experiment due to the main interest in measuring the wind flow and the importance of taking data during a cooler period.

Description of the greening systems analyzed

1. Direct façade greening system (Delft), Fig. 2a

Orientation: North-West
Plant type: climber species of *H. helix*
Plant condition: well grown and covered façade (covering thickness $+\ldots-20$ cm)
Plant age: older than 25 years  Building material façade: masonry (clay bricks)  Location: urban area

2. Indirect façade greening system (Rotterdam), Fig. 2b
Orientation: North-East
Plant type: climber species of *H. helix*
Plant condition: well grown, not completely covered façade (covering thickness $+\ldots-10$ cm)
Plant age: between 2 and 3 years old
Supporting material: steel frame/mesh
Air cavity between façade and leaves: 20 cm
Building material façade: masonry (clay bricks)
Location: dense urban area (inner city)

3. Living wall system (Benthuizen), Fig. 2c
Orientation: Western
Plant type: different evergreen plant species (no climbers)
Plant condition: well grown, not completely covered (covering thickness $+\ldots-10$ cm)
Plant age: less than 1 year old
Supporting material: planter boxes filled with soil (with thickness of 22 cm)
Air cavity between façade and planter boxes: 4 cm
Building material façade: plywood
Location: rural area

2.1. Experimental description

An experimental procedure was addressed in order to measure surface temperature, air temperature and wind velocity applicable for each greenery system (Fig. 3). Measurements were carried out on both bare and greened walls. Measurements are done on the green layer and on a bare façade next to it, to compare for each site the influence of the greenening systems. For the living wall system no bare façade was available to compare. Measurements are taken at the same height of 1.50 m and in a surface area of 1 m². Measuring points, for air temperature and wind speed, are chosen at fixed distances – 1 m in front of the greened façade, 10 cm in front of the bare and the greened façade, in the middle of the plant layer (foliage) and in the air cavity – for all the green systems; surface temperature was measured on surfaces covered with leaves, on bare surfaces and on outer and inner leaves. For the living wall system additional measurements are done behind the leaves (planter boxes) as well. In total 10 measurements are taken per site in the period of September till end of October. For each measurement 10 samples are taken and thus makes a total of 100 samples for each analyzed system; data logging per measurement take place every 15 s.

The instrumentation used for the field measurements includes an infrared thermometer and a combined wind velocity and air temperature data acquisition device. For convenience and mobility during carrying out measurements, portable measuring devices have been used for (surface and air) temperature and wind velocity measurements. The wind velocity and air temperature measurements are done with a Testo handheld hot wire probe. Surface temperatures (spot measurements) were determined using an infrared thermometer with a temperature range of $-50^\circ$C to $650^\circ$C to measure the blackbody radiation emitted from selected objects. Selected objects that are measured are: leaf surface, wall surface and planter boxes of the LWS façade.

2.2. Data processing

In order to evaluate the obtained data, a block design was used. Blocking enables to arrange the data into categories: wind speed and temperature. The category temperature is built up by dividing the data in blocks namely: highest temperature, average temperature, lowest temperature. For the category wind speed the obtained blocks are: high wind speed, average wind speed, low wind speed. The values within the blocks are presented by taking the 1 m measurements for air temperature and wind speed as starting point for a percentage comparison.

3. Results and discussion

3.1. Air and surface temperature measurements

For all the greening systems analyzed compared with the bare walls, starting from 1 m until 10 cm in front of the façades, no air temperature difference was recorded. The temperature profile for the direct greening situation shows a tendency to follow the temperature profile of the bare wall next to the green layer (Fig. 4). A small temperature difference ($\Delta T_{\text{surface}} = 1.2^\circ$C) is noticed only for the surface temperature of the bare wall compared with the direct green situation. For the indirect climber situation the tendency of the temperature profile is similar of the direct climber situation. The difference of the surface temperatures (bare-indirect green) is $\Delta T_{\text{surface}} = 2.7^\circ$C.
For the living wall system no data was available for a bare wall situation. An hypothetical line was drawn on the basis of the measurements done on the other locations to compare the temperature profile. The surface temperature difference between the hypothetical bare wall profile and the LWS façade is $\Delta T_{\text{surface}} = 5 \, ^\circ\text{C}$. The air temperature, starting from 10 cm in front of the LWS till the air cavity behind it, increases with 1.1 $^\circ\text{C}$ (see Fig. 6 and Table 3). In the case of the living wall system, compared with the other greening systems, a higher temperature difference was found; it is likely that this temperature difference is caused by 100% reduction of the sun radiation due to the materials involved.

Fig. 3. Measuring points for the vertical green systems analyzed.
The temperature profiles found for the investigated façades show no notable differences between the bare and the greened façades. This is probably due to the fact that the measurements are carried out in autumn without direct sun and with exterior surface temperatures lower than 18 °C. A research, carried out by Bartfelder and Köhler [1,2] in Berlin (Germany) during summer, shows a similar trend for low surface temperatures (respectively 16.7 °C for the bare façade and 16.3 °C behind the foliage). Differently, for warmer temperatures, it was found 31.0 °C for the bare façade and 25.2 °C for the greened façade; which indicates that vegetation has an influence on the building skin depending on the environmental conditions. Wong et al. [13] show a 4.36 °C reduction in the average temperature on the wall surface on 21 June 2008 in Singapore for an indirect climber system compared with a bare wall. Besides this, a temperature reduction behind a LWS filled with soil substrate compared to the bare wall ranges from about 2 °C at night and up to 9 °C in the afternoon. Considering the data shown by the researches, further measurements are recommended for the four seasons to get insight in the possible temperature decrease or increase thanks to a vertical greening system.

### 3.2. Wind speed measurements

The wind profile for direct greening concept shows a decrease in wind velocity ($\Delta W = 0.43$ m/s) inside the foliage compared with 10 cm in front of the bare façade. The wind velocity inside the foliage has the tendency to be nearly zero (Fig. 4). For the indirect greening system (Fig. 5) the wind velocity decreases inside the foliage as well ($\Delta W = 0.55$ m/s); however it increases inside the air cavity ($\Delta W = 0.29$ m/s). The wind velocity profile for the living wall system shows a decrease from 0.56 m/s to 0.10 m/s ($\Delta W = 0.46$ m/s) starting from 10 cm in front of the façade to the air cavity (based on a hypothetical wind velocity for a bare wall situation), as shown in Fig. 6.

The wind velocity profiles show that the foliage allows obtaining a decrease in wind velocity. The increase of the wind velocity inside the air cavity (20 cm) for the indirect climber system, which was not noticed inside the air cavity (4 cm) of the LWS façade, can be clarified through the relative thickness of the air cavity between the foliage and façade or the porosity (thickness of the foliage) of the climbing plant. Besides that living wall systems are in general made out of several dense layers (felt, plastics, soil, etc.) so there is less effect of wind penetration, as can happen for dense foliage.

The results show the potential of vertical greening layers on reducing the wind velocity around building façades. The type of greening system (direct, indirect or LWS) and its properties (foliage, porosity, materials used, etc.) influences this effect. Since the thermal transmittance (and thus insulation properties as well) of a building is among other things dependant and affected by the wind velocity that passes the surface of the building, a green façade can enhance the thermal properties of a façade.

The current standardisation for the thermal transmittance of a construction [9] assumes a wind speed of 4.0 m/s year round at the exterior surface for calculating the heat transfer coefficient (exterior surface resistance $R_e = 0.04$ m²K/W). For interior surfaces the standardisation [9] applies 0.2 m/s along the wall surface (interior surface resistance $R_i = 0.13$ m²K/W).
The thermal resistance of a construction is determined according to: \( \sum R_e + R_f + R_i \) with \( R_f \) as the sum of the thermal resistances of individual layers (materials) of the system.

For the direct greened façade a decrease in the wind speed was observed inside the foliage, from the measurements the average value of 0.08 m/s was found (90% of the 100 data points were lower than 0.2 m/s), see Table 1. For the living wall system (Table 3) the value of 0.08 m/s was found (90% of the 100 data points were lower than 0.2 m/s). When the wind speed outside is lower than 0.2 m/s (standard interior wind speed for calculation), due to the contribution of the foliage or the other layers involved (LWS), \( R_e \) can be equalized to \( R_f \). In this way the benefit on thermal resistance of the construction can be quantified by an increase of 0.09 m2K/W. This implies energy savings for building envelopes in warmer and colder climates; in addition to increasing the thermal resistance also lower surface temperatures (shaded by foliage) have an effect on the cooling capacity of buildings, especially in warmer climates.

Thermal resistance without a green layer: \( R_T = \frac{1}{R_e} \) with \( R_e \) calculated by\(^{13}\) using the following equation for greening systems an optimal air cavity thickness exist (around 40 mm), it can be noticed that also an air cavity acts like 0.5 mm of insulation material).

For the indirect greening system (Table 2) the values obtained are higher, with an average wind speed of 0.39 m/s (60% of the 100 data points were lower than 0.2 m/s); so for this situation it is not valid to equate \( R_e \) with \( R_f \). The indirect green façade system studied in this research contains an air cavity of 20 cm. It was noticed that the wind speed inside this cavity (0.39 m/s) increases again, after the foliage reduction till 0.10 m/s. Additional measurements are recommended to evaluate the influence of the air cavity thickness on lowering the wind velocity. The results of this research shows that an air cavity of 20 cm doesn’t act like a stagnant air layer, because of the higher wind speed measured; therefore it seems useful to reduce the distance between foliage and façade to obtain optimal thermal properties. Basing on the results of the wind speed inside the air cavity of the LWS (40 mm), it can be noticed that also for greening systems an optimal air cavity thickness exist (around 40–60 mm), according to building physic regulations (a 50 mm air cavity acts like 0.5 mm of insulation material).

The reduction of the wind velocity around the building envelope due to the use of a green skin has a contribution to the thermal properties of that envelope and could lead to energy savings for cooling and heating. Considering the thermal properties of the building envelope, the influence of a green layer can be higher for constructions that need to be retrofitted (low thermal resistance). However, according to the building regulation standards, any of the green systems analyzed could not replace the insulation material to fulfill the thermal resistance required. A greening system can be used in combination with (external) insulation material especially for retrofitting of existing constructions with energy efficiency problems.

### Table 1

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Fig. 6. Living wall system, temperature (left) and wind speed (right) profiles.
The benefits of vertical greening concepts discussed in this paper for the thermal behaviour have to be added to the multi-functionality of vegetation for the urban environment, with respect to the increase in biodiversity, mitigation of urban heat island effect, reduction of air pollution, production of biomass and the social and psychological well being of city dwellers.

4. Conclusions

Since the research was focussed on quantifying the wind velocity profile inside and behind the greening systems and in the possible effect on the thermal resistance; the main conclusions that can be drawn from the presented results are the follows:

- No difference was found in the air temperature and wind profiles starting from 1 m in front of the façades till inside the foliage.
- The investigated vertical greening systems are effective natural sunscreens, due to a reduction of the surface temperatures behind the green layer compared to the bare façades.
- Inside the foliage of the direct and indirect systems and inside the air cavity of the LWS a low (respectively 0.08 m/s and 0.1 m/s) wind velocity was measured.
- The higher wind velocity found inside the air cavity of 20 cm thickness of the indirect greening system demonstrates that it is also possible to speak about an optimal air cavity thickness for greening systems (around 40–60 mm).
- Due to the reduction of wind velocity measured (<0.2 m/s) the exterior surface resistance ($R_e$) could be equalized to the interior surface resistance ($R_i$). This affects the total thermal resistance of the façade which results in energy savings.

The direct greening system and the living wall system based on planter boxes are the most effective wind barriers, the reduction of the wind velocity affects the thermal resistance of the building envelope and thus his efficiency. The indirect greening system analyzed doesn’t affect the thermal resistance due to the thickness of the air cavity; it is likely that the same system with an air cavity of 40–60 mm could work as a stagnant air layer. The system with the major impact on the thermal resistance is the living wall system based on planter boxes, thanks to the “extra” created air cavity and to the thermal resistance of the other material layers involved (HDPE and soil) that can be added to the benefit of the wind velocity reduction due to the foliage. It is also possible to assume that, from a functional point of view, most of the living walls systems, compared to green façades, demand a more complex design, which must consider a major number of variables (several layers are involved, supporting materials, control of water and nutrients, etc.), on top of which they are often very expensive, energy consuming and difficult to maintain.

This study gives the possibility to calculate the energy saving for heating and cooling with several vertical greening systems, with similar characteristics to the systems as analyzed in this study.

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References