Experimental Investigation of Green Façade Components for Industrial and Storage Buildings

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Abstract. This paper deals with vertical greenery applied on the external side of lightweight walls for industrial and storage buildings. The greenery is expected to have some positive impacts on the building performance, in particular reduction of building energy consumption and peak cooling power. The achievable benefits are however dependent on local climatic conditions, hygro-thermal properties of the building enclosure, the requirements for the indoor environment and on the system of greenery applied on the walls. The side-by-side real-scale experiment involving three different test walls was built in two test windows with dimensions of 3.0 x 3.2 m. A climatic test room with controlled indoor environment is located behind test windows. Two reference walls present current standard technical solutions constructed as metal frame filled with thermal insulation with metal sheets on the exterior side, either in direct contact with core wall or with ventilated air gap. The third wall replaces the external metal sheets by the system of baskets filled by soil substrate and greenery with integrated irrigation pipes. The experiment was built in June 2019 and is extensively monitored since beginning of July 2019. Temperatures, relative humidity, heat fluxes, moisture content of soil substrate, inflow and outflow of irrigation water, and environmental boundary conditions are continuously recorded. Results of the first year of monitoring are presented and discussed in the paper. The measured results showed reduction of daily peak values of heat flux on the internal surface during hot summer days and evaluated power of evaporative cooling.

1. Introduction
Industrial and storage buildings together with shopping mall buildings often forms larger urban areas around European cities. They are characterized by a rectangular low-rise shape with large share of roof in building enclosure. Because of the accessibility by transport facilities industrial buildings are being located in parallel with highways, thus making up unpleasant view for everybody passing through. Greenery applied on vertical walls could improve the visual perception of industrial buildings, create new ecological niches for species (e.g. birds, insects) and improve acoustic properties of building enclosure.

The walls of industrial buildings are currently being constructed as lightweight structures, aiming minimal investment and maintenance costs and rapid construction process. A metal frame with thermal insulation in between the frame components is typically used in external walls. Such construction may be covered from the interior side by vapor barrier foil and plasterboard. Metal sheets are usually attached from the outside, either in direct contact with thermal insulation layer, or with ventilated air gap from rear side of metal sheets.
The green roofs and vertical greeneries improve the properties of building enclosure and the whole building performance [1]. Moreover, massive usage of green roofs and vertical greeneries within urban areas could decrease heat transfer from the building enclosures towards external environment and thus mitigate the urban heat island effect [2]. At building level, some reduction of energy needs and installation of less powerful technical systems due to reduction of peak heating and cooling loads can be anticipated [3].

The building-related benefits are influenced by local climatic conditions, hygro-thermal properties of the building enclosure (layers between greenery and interior), requirements for the indoor environment and the type of greenery mounted on the wall [4]. The reduction of energy needs is further dependent on the share of the green areas in the overall heat exchange area of the building enclosure. For storage buildings with lower thermal protection requirements, a quantifiable effect on the thermal balance of the building can be expected if sufficiently large area of greenery is involved. Understanding of the hygro-thermal interaction between the plant canopy, soil substrate and other material layers in external walls and the performance of the whole building is needed for accurate quantification of benefits and disadvantages.

Installation of greenery on the vertical walls changes the properties of the external surface of building enclosure. Less incident solar radiation is absorbed by the core wall (shading effect for incident shortwave radiation). Less long-wave radiation is radiated from the surface of soil substrate through canopy layer (shading effect for long-wave radiation). The layers of soil substrate and the greenery slightly improves thermal transmittance of the wall (insulation effect) and also increases thermal inertia of the external part of wall which reduces daily oscillation of the external surface temperature. Since the vertical greenery has to be irrigated, the latent heat of water evaporation due to transpiration through leaves and evaporation from porous substrate cools down the plants and substrate to some extent. Thermal properties of green canopy are time-dependent. Seasonal and diurnal variations of parameters can be expected. Simultaneous and coupled nature of the hygro-thermal transport processes makes difficult the quantification of individual effects [5].

This article presents side-by-side comparison of measured hygro-thermal performance of the vertical greenery system and two reference walls without greenery in real climatic conditions. Real-scale experiments exposed to ambient boundary conditions of the southwest facade were built in the University Center for Energy Efficient Buildings (UCEEB) of the Czech Technical University in Prague. In the first section of this article, the measurement setup is described. Next, an overview of the selected measured data is introduced. Then, the main findings are discussed and, finally, conclusions are drawn.

2. Materials and methods

2.1. Test cases

A climatic test room with controlled internal environment is located in University Center for Energy Efficient Buildings (UCEEB) in Buštěhrad (locality near Prague, semi-continental type of climate). Two “test windows” on the south-west facade, with the dimension 3.0 m x 3.2 m each, were used. The identical core walls (see Table 1) were built in both test windows.

Three test cases have been constructed by different arrangement of the exterior side of the identical core walls, see Figure 1. Two reference cases apply a metal sheet on the exterior side. Case S1 is metal sheet in direct contact with the core wall. Case S2 is metal sheet with ventilated air gap between the sheet and the core wall (thickness 6 cm). Cases S3a and S3b are vertical greenery distanced from core wall by ventilated air gap (thickness 6 cm) and waterproof foil. Both green walls are identical, possibly differing from each other by control algorithm of irrigation system.

Vertical greenery consists of wire baskets (30 cm × 60 cm × 10 ÷ 13 cm) filled by organic cloth and soil substrate with plants species (longer grass and flowers). Baskets are screwed to horizontal aluminum omega profiles (see Figure 2, left). The droplet irrigation system is attached in between each row of baskets (see Figure 2, right).
Table 1. Hygro-thermal properties of the core wall

| Material layers (from interior) | $d$ [m] | $\lambda$ [W/m·K] | $\rho$ [kg/m³] | $s_d$ [m] | $R$ [m²K/W] | Description |
|-------------------------------|---------|-------------------|----------------|---------|--------------|-------------|
| Plasterboard                  | 0.01    | 0.22              | 750            | 0.10    | 0.05         |             |
| Unventilated air cavity       | 0.05    | 0.50              | -              | -       | 0.10         |             |
| Vapor barrier foil            | -       | -                 | -              | 36      | -            | Polyethylene foil |
| Mineral wool                  | 0.08    | 0.06*             | 40             | 0.16    | 1.30         | Filled between grid |
| House wrap                    | -       | -                 | -              | 0.02    | -            | Vapor open foil |
| Total                         | 0.22    | >36               | 2.45           |         |              | +           |

* surface-to-surface $R$ value

* Cold bridges due to protruding metal elements were taken into considerations.

Figure 1. Left – Metal frame for the core walls, Right – External view on test facade fields

Figure 2. Left – Wire baskets with plants mounted on the facade. Right – valves of droplet irrigation system

2.2. Position of measurement sensors
The following sensors were used to monitor hygro-thermal conditions at test walls: 1) temperature sensors (Sensit TG3 (Pt1000), accuracy $\pm 0.15 \pm 0.002 \times |T|$ K), 2) temperature + relative humidity sensors (Rotronic HygroClip HC2-C04, accuracy $\pm 0.3$ K, $\pm 1$ % for 23 °C), 3) temperature and moisture content sensors (Campbell CS650 needle probe, accuracy $\pm 0.1$°C, moisture content $< \pm 3$% (accuracy is dependent on type of soil, no laboratory tests were performed for calibration prior measurement campaign)), 4) non-contact temperature sensors (infrared radiometers, Apogee SI 421, field of view 36°), 5) pyranometer (Kipp Zonen, accuracy $\pm 5$ % from measured value). Indoor air temperature and relative humidity is measured by Rotronic HygroClip HC2-S (accuracy $\pm 0.1$ K, $\pm 0.8$ %). Positions of the sensors and composition of layers are shown in Figure 3.
2.3. Operation of irrigation system

Each test field is operated by its own pipe circuit. It consists of the main vertical pipe (along the dividing column) and horizontal parallel branches placed in gaps between baskets. The inflow of water from irrigation pipes has been controlled by feedback from measured values of soil moisture content. If the median decreased below 0.3 m$^3$/m$^3$, the irrigation system was switched on for the specified time interval. The identical algorithm was used to control irrigation system of both test fields with greenery (S3a and S3b) in 2019. Functionality check of irrigation system has been performed on 15 August 2019. Naked-eye observation of outflow uniformity from irrigation pipes was performed when irrigation system was switched on for approximately 10 minutes. The irrigation system was deactivated on 29 October 2019 (rest period for plants).

3. Results and discussion

3.1. Water balance

Balance equation expressing conservation of mass was used for estimation of daily evapotranspiration and the associated latent heat of water (2.5×10$^6$ J/kg):

$$\frac{\Delta m_w}{\Delta t} = q_{in} - q_{out} + q_{DR} - g_{ET} \quad [\text{kg/(m}^2\text{day) }]$$ (1)

where $\Delta m_w/\Delta t$ is change of mass of water in soil substrate during time interval, $q_{in}$ is measured inflow from irrigation system, $q_{out}$ is measured outflow of water from test field (water collected by trough placed beneath test field is fed through tipping rain gauge), $q_{DR}$ is driving rain on test field and $g_{ET}$ is evapotranspiration from surface of substrate and surface of leaves. Mass flows are related to outside aperture of greenery (1.4 m × 3.0 m). Please note that estimation of $\Delta m_w/\Delta t$ component might be associated with errors due to sensor accuracy, limited sensing volume of the moisture content pin and limited number of sensors buried in soil baskets.

Since outflow from test fields and driving rain were negligible in August 2019 the evapotranspiration flow was simplified as:

$$g_{ET} \approx g_{in} \frac{\Delta m_w}{\Delta t} \quad [\text{kg/(m}^2\text{day) }]$$ (2)

Components of water balance, daily mean values of moisture content and daily mean values of latent heat flow and global solar irradiance during August 2019 are shown in Figure 4.
Figure 4. Water balance components, daily mean values of latent heat flux due to evapotranspiration ($q_{ET}$) and global solar irradiance measured on the plane placed in parallel with test facade ($G_{Gt}$).

Daily amount of 2 – 3 liters per square meter and day was needed to keep desired mean value of moisture content of soil substrate during August 2019 (see Figure 4, top). It is seen that if regular irrigation is applied, daily evapotranspiration rate is approximately equal to daily water inflow ($\frac{\Delta m_w}{\Delta t} \approx 0$). Daily evapotranspiration of 2 – 3 liters per square meter corresponds to daily mean latent heat flux - 54 W/m$^2$ resp. - 87 W/m$^2$. Heat extraction due to evapotranspiration thus compensate for incident solar irradiance to considerable extent (see Figure 4, bottom).

At the beginning of experiment (in July) 3 – 5 liters per square meter and day were fed into test fields with greenery. The soil substrate was not capable to retain water and water dripped from basket to basket. Part of inflowing water was not used. The cooling effect of evaporation is therefore practically limited by retention capacity of the soil substrate.

Systematic difference between readings of moisture content sensors (see Figure 5) was initially attributed with non-uniform flow in parallel branches of irrigation pipes. Visual inspection of outflow (performed on 15 August 2019) did not show up clogged outlet valves. The reason for non-uniform moisture content in the test field was not found.

Soil substrate was difficult to maintain at similar levels of moisture content and physical condition of plants. Large green fields might suffer from even stronger variation of moisture content. Hydraulic loops of irrigation system should be designed with care so that it can to some extent counterbalance possible non-uniformity of moisture within larger field of vertical greenery.
3.2. The impact of greenery on the core wall

3.2.1. The exterior side
Temperature in ventilated air gap temperature (midpoint) measured in cases S2, S3a, S3b, surface temperature of metal sheets (S1), and external air temperature ($T_{ae}$) during first two weeks of August 2019 is compared in Figure 6. Since temperatures in air gap of cases with greenery S3a and S3b were very similar, solely temperature of case S3a is depicted.

The surface temperature of metal sheet placed in direct contact with the core wall (case S1) exhibited very high peak daily values. The surface temperature of the sheet depends in this case mainly on heat flow towards the external environment since thermal insulation in the core wall effectively decrease heat flow towards interior. Peak daily surface temperatures of the sheet approached 60 °C in clear sky conditions. The peak daily difference between surface temperature of metal sheets and ambient air temperature exceeded 25 °C in a day with clear sky conditions.
Temperature measured inside the ventilated air gap of case S2 was also higher than temperature of ambient air. Peak daily temperatures in ventilated air gap exceeded 35 °C in clear sky conditions. The peak daily difference between ventilated air gap temperature of case S2 and ambient air temperature typically approached 5 °C in clear sky days. Ventilation of air gap by outdoor air was capable to extract the significant part of solar heat gains.

Air temperatures in the ventilated air gap behind the green facades (case S3a) were lower than ambient air temperature during the first half of the day (direct sun enters the test facade after 12:00). Green facade was capable to cool air in the gap to some extent (see temperature difference in Figure 6). The air temperature was close to the ambient air temperature even when direct solar radiation was irradiating the wall. The air gap temperature was slightly higher than the ambient air temperature during the night hours. This effect can be attributed with heat stored in soil substrate over the preceding day and insulation effect of plants. The daily mean of temperature difference between air gap temperature and ambient air temperature was close to zero.

3.2.2. The interior side
Heat flux measured on the internal surface of the core wall during first two weeks of August 2019 is compared in Figure 7.

The peak daily values of heat flux on the internal surface of test walls with greenery are reduced. Reduction of daily peak value is more pronounced if the green walls are compared with the unventilated reference wall (case S1). In this case, the difference of peak values approached 3 W/m² in days with clear sky. If the green wall is compared with case S2, the difference was approximately halved. Thermal benefits of greenery are dependent on the thickness of thermal insulation layer in the core wall.

The results should be put in perspective of the whole building. A green wall with area of 1000 m² could decrease thermal load by 3000 Watts if compared with equally large wall of case S1. An unshaded inclined skylight with area of 6 m², directed towards sun, could induce comparable thermal load into the building. Heat load reduction due to greenery applied on the walls can be easily outperformed by inappropriate design and operation of transparent building components, and by internal loads which are often the main contributors in thermal balance of industrial buildings.

4. Conclusions
The hygro-thermal performance of typical light-weight walls for industrial buildings was studied by means of real-scale experiment in semi-continental climate (locality near Prague, Czech Republic). The performance of green walls was compared side-by-side with the reference walls without greenery.

If the wall with greenery is compared with the reference wall with unventilated metal sheet on the external side, the daily peak values of heat flux on the internal surface during hot summer days were
reduced by 3 W/m$^2$. If the wall with greenery is compared the reference wall with ventilated metal sheet on the external side, the reduction of daily peak values of heat flux was approximately halved.

Evapotranspiration was calculated from measured inflow and moisture content of soil substrate. Daily mean values of latent heat flux up to -100 W/m$^2$ were observed in warm days. Despite evaporative cooling and shading effect of plant cover, air temperature in the ventilated air cavity between greenery and the core wall was not significantly below the temperature of ambient air.

Finally, it should be noted that installation of greenery on vertical walls requires some technical effort (supporting structure, substrate with plants, irrigation and control system). Currently, it is associated with extra costs, use of raw materials and maintenance costs. Any fault detection of irrigation system, checking of plant condition, pruning and cutting is difficult due to necessity of work on lifting platform.

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