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Influence of an active living wall on indoor temperature and humidity conditions

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ABSTRACT

Living walls are systems that allow the development of vegetation in a vertical surface attached to building facades or indoor walls. Traditionally, they have behaved as 'passive' bio-filters, but new approaches and technologies are moving towards their integration within the building's air conditioning and ventilation systems. In an Active Living Wall (ALW), air is forced to pass through the vegetated wall to take advantage of their evaporative cooling potential as well as the capacity of these biological systems to purify air. In the case of indoor ALWs, air is cooled, bio-filtered and humidified thus potentially reducing ventilation requirements. This work describes a prototypic indoor ALWs installed at the University of Seville (Spain). Preliminary results of its performance on indoor air conditions (temperature and humidity) are presented and discussed. Drops in temperature between 0.8 and 4.8 °C have been observed at different distances from the ALW. The cooling process was more efficient when the initial conditions of the room were drier and warmer.

1. Introduction

Vertical gardening is an innovative urban greening technique, a new trend that is presented as an alternative to traditional systems of landscaping and construction with a great number of ecological and performance benefits. It basically involves the design and construction of vegetated areas in a vertical plane. The main benefits of 'vertically greening' the buildings are, among others: mitigation of the heat island effect in cities (Wong et al., 2010); passive cooling of buildings by means of shading the walls and increasing the thermal insulation of the building envelope (Perini et al., 2011; Kontoleon and Eumorfopoulou, 2010), or biodiversity enhancement (Dunnett and Kingsbury, 2004; Blanc, 2008). There are also numerous advantages if these vertical greening systems are used inside buildings such as indoor air purification or biofiltration (Soreanu et al., 2013), retention of suspended particles (Ottelé et al., 2010) or fixation of CO_2 and VOCs (Currie and Bass, 2005).

The simplest vertical greening systems are based on the use of climbing plants, but there are other more complex, commonly called living walls, in which plants grow directly on the vertical surface (Kontoleon and Eumorfopoulou, 2010). Some are based on hydroponic cropping systems, which use a support structure providing an inorganic substrate where plants are inserted, favoring the root spreading. Though living walls usually act as passive elements, an air flow can be forced through the substrate and plant rooting system, becoming an active living wall (ALW). By using these most advanced systems, the benefits above mentioned are enhanced and the effects on the conditions of indoor temperature and humidity and air quality – active biofiltration (Soreanu et al., 2013) – are more remarkable (Darlington et al., 2000; Meier, 2010).

In warm climates with periods of low air humidity, these systems can be used as natural evaporative coolers and obtain reductions in air temperature. This is achieved by an evaporative adiabatic saturation process in which the ALW acts as a mass and heat exchanger, lowering the temperature and increasing humidity (Darlington et al., 2000; ASHRAE, 2009) as air passes through the porous substrate and vegetated surface. Though the reduction of air temperature obtained may be minor, the fact that the building's air conditioning system will have to overcome a lower difference between comfort and ambient temperatures could result in energy savings. Also, the contribution of ALWs to improve indoor air quality through active biofiltration may reduce the ventilation requirements and thus the heating and cooling energy needs of the building (Rodgers et al., 2013). This work aims to describe a prototypic indoor ALW and empirically quantify its close-range effect on air temperature and humidity (thermal comfort factors) inside a Mediterranean building.

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2. Material and methods

2.1. Description of the ALW prototype

The ALW prototype used for this experiment (Fig. 1) is located in the main hall of the School of Agricultural Engineering (University of Seville, Spain). The system comprises a metal structure of galvanized steel 1.7 m wide, 3.5 m high and 0.3 m thick, with a vegetated air filtering surface of 8 m^2. It is fixed to the wall and lies on a prismatic steel tank with a maximum water capacity of 0.54 m^3. The front and two laterals of the structure are covered by a textile fabric, while the back and top are covered by a rigid sheet of polycarbonate. The textile fabric is composed by two layers of polyamide (outer layer) and polypropylene (inner layer) with a total thickness of 15 mm. Those layers are sewn together forming pockets of 0.125 by 0.125 m in which plants are inserted. Therefore, this fabric acts as a porous medium to support vegetation development and to enhance the epiphytic growth of plants. It also facilitates the air flow through it, increasing the contact between crossing air and water (Franco et al., 2012). The recirculation irrigation system consists of two PVC pipes (diameter of 0.02 m) placed at the top and the middle of the ALW with holes (diameter of 0.0015 m) spaced 0.025 m from each other. They are supplied by a PVC vertical pipe connected to a submersible 400 W pump placed in the tank. The system is also equipped with an UV lamp filter and a mesh filter. Four HXBR/2-250 axial fans (S&P Sistemas de Ventilación, S.L.U, Parets del Vallés, Barcelona, Spain) with a maximum air flow of 0.46 $m^3 s^{-1}$ (120 W) are placed in the upper part of the ALW. They take warm air from the upper part of the hall which is forced into the ALW where it will pass through the vegetated layer. A metal halide reflector (200 W) was used to provide supplemental artificial lighting when natural light was not enough for the plants. Irrigation events and cycles of artificial lighting were automatically scheduled, while the fan system was operated manually. The main species planted in the ALW are: *Asparagus sprengeri* Regel, *Chlorophytum comosum* (Thunb.) Jacques, *Epipremnum aureum* (Linden ex André) G.S.Bunting, *Ficus pumila* L., *Monstera deliciosa* Liebm., *Nephrolepis exaltata* (L.) Schott, *Soleirolia soleirolii* (Req.) Dandy and *Spathiphyllum wallisii* hort.

The dimensions of the hall where the ALW is installed are approximately 9 m wide, 12 m long and 3.25 m tall. It has two corridors, stairs to the second floor and the main door. There is not a central HVAC system for the building so this hall does not present any means of air conditioning apart from the ALW.

2.2. Assessment of the ALW performance

The ALW performance was assessed under summer conditions by conducting experiments over two days differing in their air humidity levels. The experiments were performed more than one year after plantation of the ALW to ensure that vegetation had completely covered the ALW. The experiments were conducted during weekend days in order to avoid any alterations caused by the opening of the entrance door and people passing by. It should be noted that when the building is occupied, the results may vary slightly due to the proximity of the ALW to the hall main entrance. The ALW fan system was activated (with the fans running at full power) once per day to perform a cooling cycle (lasting three hours the first experimental day and two hours the second day).

2.3. Data collection and treatment

Measurements of air temperature (T) and relative humidity (RH) were performed using a set of 10 sensors model HOBO Pro Temp-HR U23-001 (Onset Computer Corp., Bourne, Massachusetts, USA) distributed as depicted in Fig. 1. T and RH values were recorded at different heights and horizontal distances from the ALW. The sensors act as autonomous dataloggers so they were programmed to register data every 10 s. Room T and RH were also recorded at the middle of the hall (3 m from the ALW).

Air actual vapor pressure (e_a) was calculated as:

$$e_a(\text{kPa}) = \text{RH}(\%)e_{\text{sat}}(\text{kPa})0.01$$

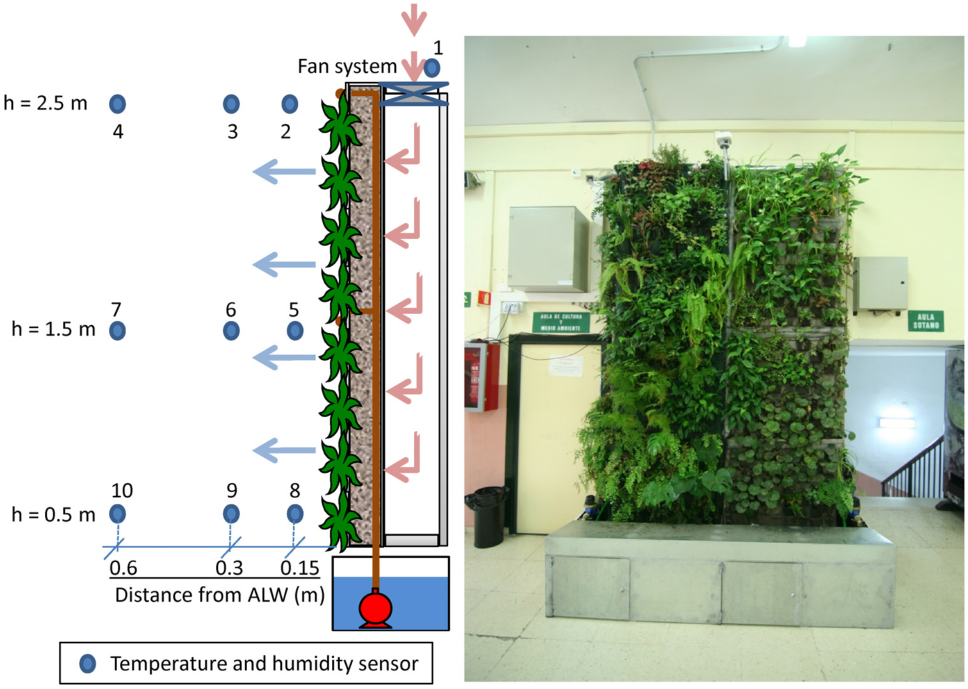

Fig. 1. ALW prototype and experiment setup.

where, e_{sat} is the saturated vapor pressure at the dry-bulb temperature. e_{sat} was determined from:

$$e_{sat}(\mathrm{kPa}) = 0.6107e^{\left(\frac{17.27T}{T+237.3}\right)}$$

where, T, in °C, is the dry-bulb temperature. The saturation efficiency (η), which characterizes the saturation capacity of the ALW system, was estimated by the following expression:

$$\eta(-) = \frac{T_{in} - T_{out}}{T_{in} - T_{wb}}$$

where, T_{in} and T_{out}, in °C, are the inlet and outlet dry-bulb temperatures, and T_{wb} (°C) is the wet-bulb temperature of inlet air which was approached as (Stull, 2011):

T_{wb} (°C)=T atan[0.151977(RH + 8.313659)$^{1/2}$]+atan(T + RH)−atan (RH − 1.676331)+0.00391838·RH$^{3/2}$ atan(0.023101·RH)–4.686035 with relative humidity (RH) in %.

3. Results and discussion

Fig. 2 shows T and RH values recorded during both experimental days at the center of the hall (T_hall and RH_hall), at the same height closer (0.3 m apart) to the ALW (T_ALW) and at the air intake in the upper part of the ALW (T_intake). T values showed a similar pattern during both days but it is interesting to note that, even when the ALW fan system was not functioning, T_ALW was 0.6–1.3 °C lower than T_hall during day 1 and 0.8–1.5 °C lower during day 2. This is possibly explained by the cooling effects of vegetation transpiration and water evaporation from the tank placed underneath the ALW. That is consistent with previous observations in a passive living wall (Fernandez-Cañero et al., 2011). In day 2, the cooling effect was enhanced as compared to day 1 due to the drier conditions of that day (denoted by lower RH as compared to day 1). The ALW cycles had a marked influence on indoor air T and RH, though the cooling effect was more evident in the proximity of the ALW. Approximately one hour after switching the ALW fan system off, T and RH gradually recovered their previous state.

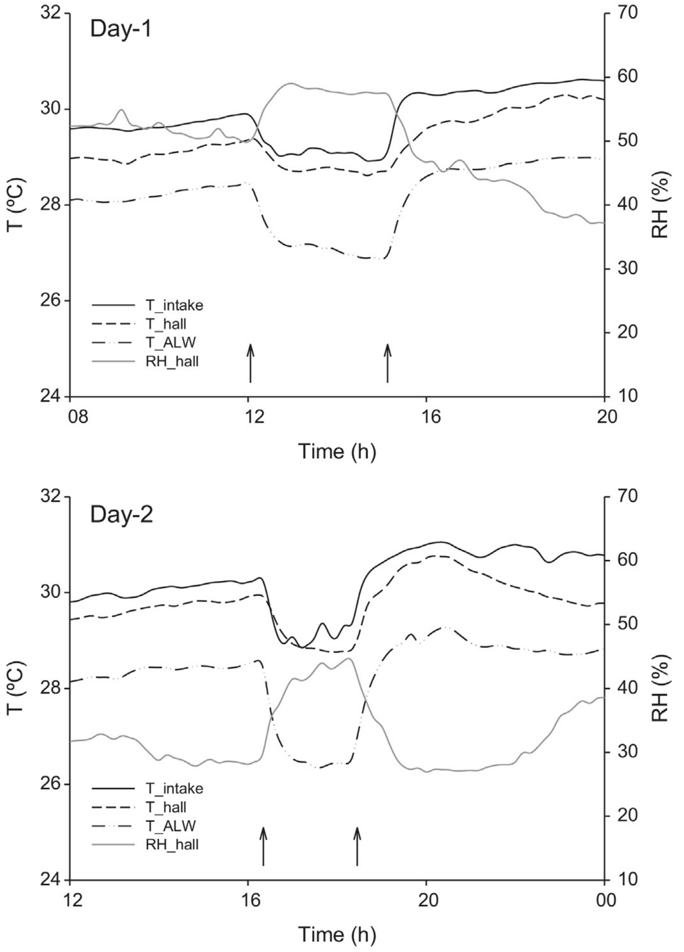

Fig. 2. Indoor air temperature (T) and relative humidity (RH) during two different summer days. T_intake: air temperature at the ALW air intake (#1 in Fig. 1); T_hall and RH_hall: air temperature and relative humidity, respectively, at the center of the University hall; T_ALW: air temperature at the same height as T_hall but closer (0.3 m apart) to the ALW. The vertical arrows delimit the periods when the fan is on.

Fig. 3 shows T and RH values measured at two horizontal distances from the ALW (0.15 m and 0.6 m) and at three different heights (0.5 m, 1.5 m and 2.5 m). Both variables were also registered for the air entering the ALW (intake) at a height of 2.75 m. The significant vertical gradient of T observed before, during and after the cooling cycles is remarkable. Near the ALW (horizontal distance of 0.15 m), a higher drop in T (accompanied by an increase in RH) was observed at the height of 2.5 m compared to other heights. This may occur due to the air flow distribution coming out of the ALW where the upper part, closer to the fan system, expels a higher cool air flow which is consistent with the air speeds measured at different heights (Table 1). This effect is not observed at 0.6 m of distance from the ALW as the T vertical gradient has already been rearranged.

During the ALW cycles, the temperature reduction occurred mainly during the first 15–20 min, and after that T reached a plateau until the fan system was disconnected. These results suggest that longer periods of ALW operation do not imply higher drops in temperature, although this may depend on others factors as the ALW size or the volume of air to be treated.

Table 1 shows the mean air temperature decrease (ΔT), respect to pre-cooling air temperature measured at the same height, at two horizontal distances from the ALW (0.15 m and 0.6 m) and at three heights (0.5 m, 1.5 m and 2.5 m) over both cooling cycles. ΔT ranged between 0.8 °C and 4.8 °C and between 0.8 °C and 2.3 °C at a horizontal distance of 0.15 m and 0.6 m, respectively.

The existing vertical gradient of air temperature makes it difficult to compare air temperature of inlet air (taken at height = 2.75 m) with the values recorded at lower heights. Saturation efficiency (η) was, therefore, only estimated for the upper part of the ALW system (height = 2.5 m), where pre-cooling temperatures are closer to those of inlet air. The preliminary results derived for our prevalent conditions show that η ranged within the interval 0.36–0.46, the lower the actual vapor pressure of air, the higher the saturation efficiency. The greater temperature reductions observed during cycle 2 are probably due to a higher value of η obtained in that period as a consequence of warmer and drier air conditions.

Table 1
Mean T decrease (ΔT) and air speed (AS) measured over two cooling cycles at different horizontal distances from the ALW and heights. Saturation efficiency (η) of the system was approached with measurements performed at 0.15 m (horizontal distance) and 2.5 m (height). e_a and RH denote mean actual vapor pressure and mean relative humidity, respectively, of inlet air over the cooling cycles.

		Cycle 1 Height (m)			Cycle 2 Height (m)		
Variable	Distance to ALW (m)	0.5	1.5	2.5	0.5	1.5	2.5
ΔT	0.15	1.2	0.8	2.8	1.6	1.1	4.8
	0.6	1.7	1.6	0.8	1.9	2.3	1.2
AS (m s^{-1})	0.15	0.05	0.31	0.33	0.13	0.32	0.60
	0.6	0.16	0.42	0.15	0.21	0.38	0.21
η			0.36			0.46	
e_a (kPa)			2.1			1.5	
RH (%)			51.4			37.4	

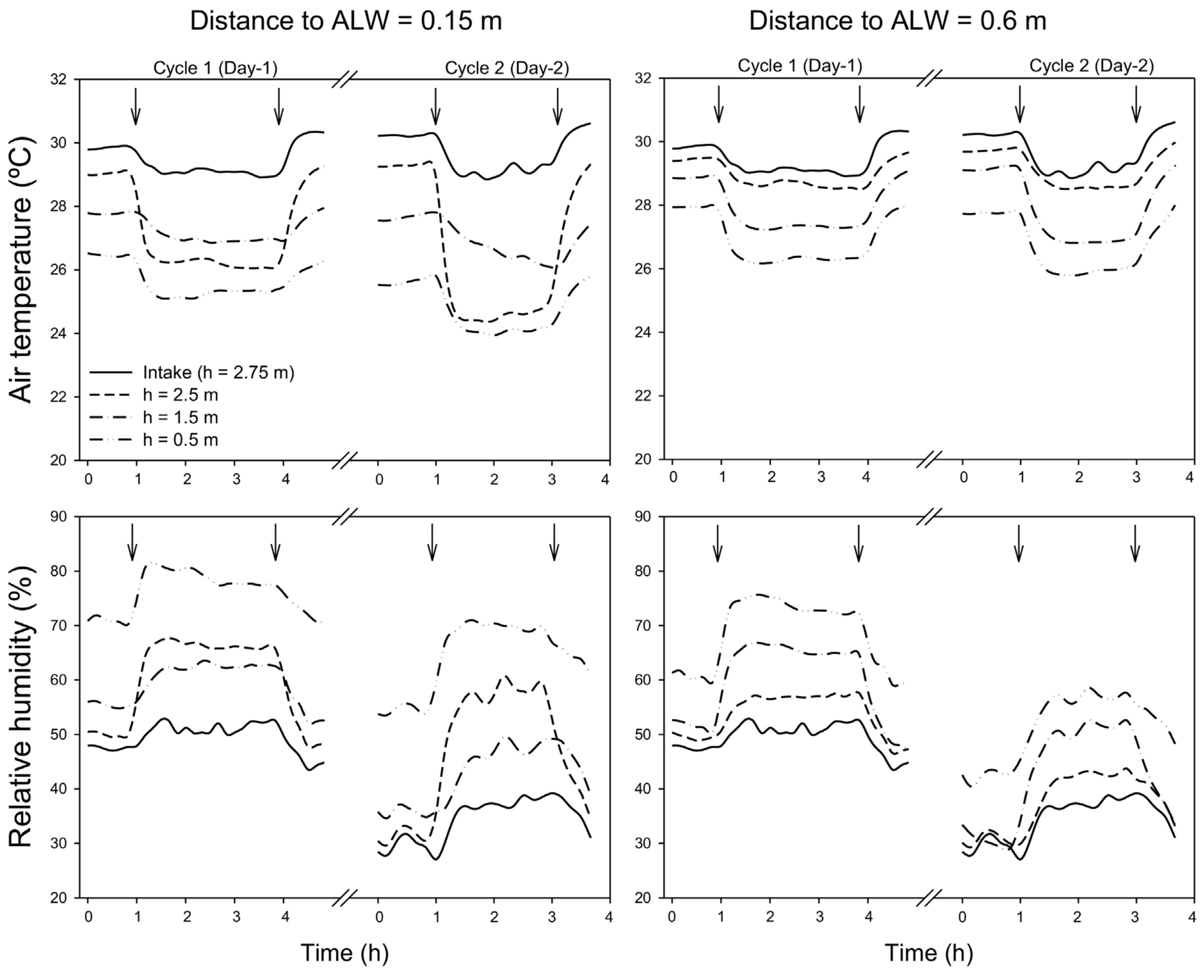

Fig. 3. Air temperature and relative humidity measured at different horizontal distances from the ALW and heights over two cooling cycles. The legend in the upper-left panel is common to all panels. The vertical arrows delimit the cooling cycles.

4. Conclusions

This work presents promising results on the potentiality of ALWs to contribute in the process of indoor air conditioning in a more ecofriendly way, which joined to their demonstrated capacity to improve air quality makes ALWs an attractive option to be further explored for sustainable construction. Indeed, there are still important knowledge gaps to optimize the performance of these systems (e.g., plant species selection, materials, ALW size in relation to volume of air, etc.) or their impact on air quality or the energy balance of a building.

In this study, drops in temperature between 0.8 and 4.8 °C have been obtained at different distances from an ALW. As it could be expected, the cooling process has proved to be more efficient when the initial conditions of the room are drier and warmer. According to the reduced ALW impact observed in the center of the hall, against the higher impact observed close to the ALW, our results suggest that the ALW surface (the one covered by vegetation) was underestimated for the air volume contained in the hall. Therefore, further experiments to optimize the size of ALW systems according to the volume of air to be conditioned are essential.

An alternative to the experimental design described in this study, i.e., air flow is forced to cross the vegetated layer from the inside to the outside of the ALW, would be to invert the process by forcing the air flow to pass the vegetation layer from the outside to the inside of the ALW. This other configuration may allow some advantages as diverting the treated (cooled, biofiltered) air to the building HVAC system in order to reduce the volume of outdoor air that needs to be cooled and ultimately energy consumption.

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