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Measurement of air flow through a green-wall module

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Abstract

Green or living walls are active bio-filters developed to enhance air quality. Often, these walls form the base from which plants are grown; and the plant-wall system helps to remove both gaseous and particulate air pollutants. A green wall can be found indoors as well as outdoors, and could be assembled from modules in an arrangement similar to tiling. Measurement of air flow through such a module has been conducted in this work. The module is essentially a rectangular plastic box (dimensions about 500 mm x 500 mm x 130 mm) that holds a permeable bag containing a plant-growing medium (replacement for soil). The front face of the module has multiple openings for plants to protrude out from the bag inside. Plant roots are imbedded in the medium. A fan positioned at a central opening on the module's back face drives air through the medium-plant-roots mix and then onward through the plants' canopy; and these would help to remove both gaseous and particulate pollutants from the air. Drip-irrigation water is dispensed from a tube running along the open top-face of the module. The module has also a small drainage hole on its bottom face. Pressure drop across the module, air-flow distribution through it as well as flow rate have been obtained, in terms of variable parameters which include moisture content, growing-medium-plant-roots mix and plant type. The measurements help to determine the pattern of flow resistances which in turn will be used in a future CFD (Computational Fluid Dynamics) analysis for improving the design of the module, such that more appropriate flow distribution and flow rate would be achieved. All this is in addition to the better understanding of air flow through complex moist porous media.

Nomenclature

Symbols

A: Area
B: A constant
C: A constant
D: Diameter
K: Loss coefficient
P: Gauge pressure reading taken at module's back-opening [Pa]
Q: Total air flow rate through module [l/s]

Subscripts

F-L: Funnels, large
F-S: Funnels, small
Free: No funnels used; the module is free
Dry: Dry condition
Wet: Wet (saturated) condition
S: Plant-growing medium (Soil replacement)

Introduction

Green or living walls are composed of vertical modules fixed vertically to a structure wall or frame. They can be made of various types of material and support a wide variety of plant species [5]. They can produce changes in the ambient conditions (temperature and humidity) of the air layers around them which create an interesting insulation effect [7]. Living walls modules provide an inorganic substrate into which the plants are inserted. They can be classified as passive or active systems [4]. The active systems are designed with ventilators which force air through the substrate and plant rooting system, therefore the air is purified and filtered in a process known as bio-filtration [2] which also acts as a natural cooling system. Living walls can be found both indoors and outdoors. They are of great beauty and have numerous energy benefits since the ventilation requirements are reduced due to the bio-filtrated air [3]. Their benefits include temperature reduction, improvement of air quality and reduction of air pollution, lowering levels of VOC (Volatile organic compounds) [1], oxygen production as well as the social and psychological wellbeing [8].

In the interests of developing green wall technology for sustainable indoor air quality maintenance, an active, modular green-wall system, the 'Breathing Wall', is developed in collaboration with Junglefy Pty Ltd (Sydney, Australia). The addition of assisted aeration through the plant's growing substrate (often described in the literature as 'active botanical bio-filtration') was made with the primary function of filtering particulate matter and increasing removal of VOCs. Preliminary work has demonstrated the system is capable of substantial reductions of PM_{10}, $PM_{2.5}$ (particulate matter with 10μm and 2.5μm in diameter and smaller) and VOCs within an enclosed environment [9]. These benefits notwithstanding, knowledge on the air flow through the substrate and back pressure remains unknown, preventing further development of the technology utilised. The ultimate aim of this research is to evaluate the air flow through a plant-based active green wall system, designed to maintain a healthy and sustainable indoor environment.

The long-term objective of this study is to improve the air flow distribution and hence the efficiency through the breathing wall modules and their surroundings, using future CFD (Computational Fluid Dynamics) methods verified with empirical data collection. To obtain the correct parameters, which include the various resistances to flow that are needed for reliable CFD modelling, experimental work is conducted in this work that includes measuring the air flow rate and the pressure differential across the module. To achieve this it was essential to acquire the necessary set up to measure the low flow rate out of the module and to calibrate all the instruments used to ensure that they are reliable and accurate. Due to the very low velocity of the air flow after passing through the green wall module, funnels were used to help measure the air velocity of the air and correspondingly calculate the total flow rate.

Materials and Methods

The main objective here is the measurement of air flow through a green module. The pressure drop across it is also obtained. The module is essentially a rectangular plastic box (dimensions about 500 mm x 500 mm x 130 mm) that holds a permeable bag containing a plant-growing medium (replacement for soil). The front face of the module has 16 openings for plants to protrude out from the bag inside. Plant roots are imbedded in the medium. A fan positioned at a central opening on the module's back-face drives air through the medium-plant-roots mix and then onward through the plants' canopy; and these would help to remove both gaseous and particulate pollutants from the air. Drip-irrigation water is dispensed from a tube running along the open top-face of the module. The module has also multiple small drainage holes on its bottom face. All front and back openings are circular with diameter 100 mm. Figure 1 shows a typical such module.

Figure 1. A green-wall module with plants (Schefflera arboricola) protruding out from a bag containing plant-growing medium inside. The plant used in this work was Chlorophytum comosum variegatum, however.

Because of the very high resistance to air flow by the bag with its content of mixture of plant-growing medium and plant roots, air velocity coming out of the module's outlet openings (front, top and bottom) is very small. On the other hand, there is much flow reversal in the fan-and-duct assembly connected to the back opening; this makes any flow measurement through the back opening not feasible. Similarly, because of strong flow reversal, it's not feasible to simply read off the flow rate against pressure from a manufacturer fan-performance-curve. Thus, so as to increase the flow velocity to measurable levels, funnels are used to cover all of the module's outlets.

Acrylic sheets were used to form rectangular-box chambers of 20-mm height at the top and bottom faces of the module. Circular holes of size similar to the front-face openings' were cut out on the chambers' outer face, and funnels are also fitted to these holes for air-velocity measurement. Three holes were cut out at the top-face chamber and one hole at the bottom-face one. Thus air exits from the module via 20 openings (16 at front, 3 on top and 1 at bottom) and funnels are fitted to all these circular openings for increasing air velocity to measurable levels. The module with its funnels in place is shown in Figure 2.

A Cole Parmer hot-wire thermo-anemometer was used to measure the air velocity and temperature. The probe was securely placed normal to the air-flow direction approximately 2 cm from the funnel exit (see Figure 2). But before this position was chosen, it was verified that as the distance between the probe and the funnel exit varies from 0.5 cm to 3 cm, and over a period of several minutes, the readings were fairly constant, fluctuating by less than 6% about the mean values.

Figure 2. Green-wall module with funnels attached (16 covering the front openings, 3 on top and 1 at bottom). The hot-wire velocity probe can be seen at the black right end of the silver-colour horizontal handle; the handle itself is mounted on an aluminium vertical post seen at the left of the module.

In addition to the manufacturer's specifications relating to the anemometer's accuracy and reliability, its readings were further verified for low speeds using a trustworthy and visible mechanism which is a rotating circular disk driven by a motor with variable speeds. The probe was placed on the rim of the disk and the speed recorded by the anemometer was compared to the disk's speed; the difference between the readings is less than 5%.

The fan used in this work is a constant-speed FANTECH TEF-100 which is a 16-W in-line axial fan, fitted to 100-mm-diameter duct at each end.

Pressure difference was measured with a Sensirion digital-sensor SDP610 – 125Pa. It is 0.1-Pa accurate for low differential air-pressure up to 125 Pa. Values were recorded every second and the average value was then calculated from a data logger.

In addition to the manufacturer's guarantee, a closed-loop wind-tunnel is used for verifying further the readings of the pressure-differential sensor. Thus the sensor is connected in parallel with an inclined manometer which gives the pressure difference from a Pitot-static tube placed in a wind tunnel. Measurements were recorded at 9 different speeds of the wind-tunnel motor. An excellent linear relationship was obtained between readings from the digital pressure-sensor and the inclined manometer, as shown in Figure 3. This gives extra confidence in the digital pressure-sensor used. Figure 3 is then used to get the actual pressure difference from the sensor readings. When air exits from the module, whether funnels were used or not, it exits to the ambient. Thus readings from the digital sensor for (gauge) pressure at the module's back-opening are also the pressure difference across the module. During a course of recording which typically lasts several minutes, pressure readings vary by less than 10% about an average value.

In the following, all reported readings (pressure and air velocity) are averages; and all pressures are (gauge) pressure readings taken at the module's back-opening.

The plant used in this work was Chlorophytum comosum variegatum.

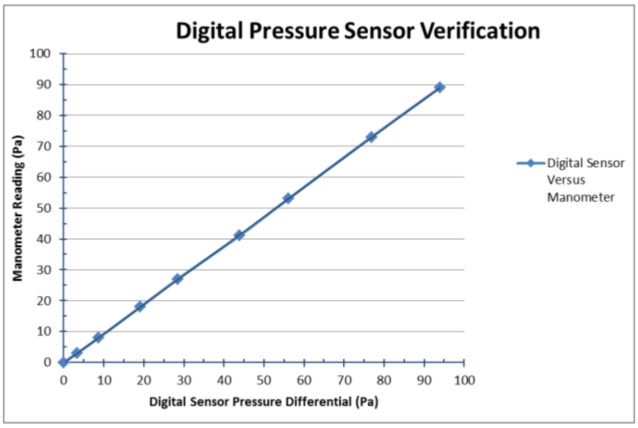

Figure 3. Digital Pressure Sensor Verification

As mentioned, because of the very low velocity of the air coming out of the modules' openings, funnels were used to increase the velocity to measurable levels. Two sets of funnels with exit-opening (smaller) diameter of 17.8 mm and 14.5 mm were used. The funnels' larger openings are slightly larger than 100 mm in diameter, thus totally covering the modules' 100-mm-diameter openings. Velocity of the air is thus increased by $(100/17.8)^2$ and $(100/14.5)^2$, or 32 and 48 times respectively, as it moves from the modules' openings to the funnels' exit.

To obtain the total air-low rate Q_{Free} across the module (without any funnel, hence air velocity at module's openings is too low to record) the following measurements were taken (see Nomenclature for definitions of terms): P_{Free}, $P_{F\text{-}L}$, $P_{F\text{-}S}$, $Q_{F\text{-}L}$, and $Q_{F\text{-}S}$

The Q_{Free} is obtained from the following approximate analysis

With the air driven by the fan through the module with large funnels covering its openings, the following approximate energy relation is used

$$P_{F\text{-}L} = C\,(K_S + K_{F\text{-}L})(Q_{F\text{-}L})^2 \quad (1)$$

Similarly, with small funnels covering the module's openings

$$P_{F\text{-}S} = C\,(K_S + K_{F\text{-}S})(Q_{F\text{-}S})^2 \quad (2)$$

And when the module is free (no funnels used)

$$P_{Free} = C\,(K_S)(Q_{Free})^2 \quad (3)$$

But when flow undergoes a contraction (like through a funnel) the loss coefficient K is known to decrease with the area ratio (A_{Small} / A_{Large}) or square of diameter ratio $(D_{Small} / D_{Large})^2$ [6]. Here D_{Large} is taken to be the module-opening diameter which is fixed (100 mm) and D_{Small} the funnel's exit diameter.

Assuming the decreasing relationship between K and $(D_{Small})^2$ to be $K = B / (D_{Small})^2$

Then $K_{F\text{-}L} = B / (D_{F\text{-}L})^2$ and $K_{F\text{-}S} = B / (D_{F\text{-}S})^2$ (4)

Substituting (4) into (1) and (2), the product of constants C×B can be obtained from measured values of P, Q, and D associated with large funnels and small funnels. (1) or (2) then gives $C.K_S$

Using $C.K_S$ in (3) Q_{Free} can then be obtained from measured value of P_{Free}.

Results and Discussions

Total air-flow rate through the module and the corresponding pressure difference across it were obtained for the following 4 cases of the content of the module's internal bag:

A) Dry, unplanted: DRY plant-growing medium only
B) Wet, unplanted: WET (saturated) plant-growing medium only
C) Dry, planted: Plant roots imbedded in growing medium, in DRY condition
D) Wet, planted: Plant roots imbedded in growing medium, in WET (saturated) condition

The following measurements of P_{Free} , $P_{F\text{-}L}$, $P_{F\text{-}S}$, $Q_{F\text{-}L}$ and , $Q_{F\text{-}S}$ have been obtained as shown in Table 1 and Table 2.

Using the calculation procedure above, the total air-flow rate Q_{Free} through the module corresponding to its free openings (without any funnels used) has also been obtained, and shown in Tables 1 and 2.

Unplanted Module 2 Sets of 20 Funnels	**Dry Unplanted Module**		**Wet Unplanted Module**	
	Press. Diff. (Pa)	**Total flow (Lit/sec)**	**Press. Diff. (Pa)**	**Total flow (Lit/sec)**
Free Openings	**20.06**	**9.10**	**24.47**	**15.79**
Large Funnels	22.16	8.72	26.10	8.60
Small Funnels	23.45	8.61	29.59	7.84

Table 1 - Summary for Dry and Wet Unplanted Module Values

Planted Module 2 Sets of 20 Funnels	**Dry Pllanted Module**		**Wet Planted Module**	
	Press. Diff. (Pa)	**Total flow (Lit/sec)**	**Press. Diff. (Pa)**	**Total flow (Lit/sec)**
Free Openings	**16.44**	**10.00**	**18.38**	**14.90**
Large Funnels	18.79	9.29	21.33	9.55
Small Funnels	20.27	9.10	25.26	9.02

Table 2 - Summary for Dry and Wet Planted Module Values

First, it's noted that the Q-P relationship (curve of flow-rate versus pressure) in all cases has trends agreeing with typical fan performance curves', namely as Q increases, P decreases.

Note also that no case with a plant canopy was considered. First, because of the use of funnels, plant canopy had to be cut off. Second, plant canopy was seen to offer very little resistance to flow. Thus, pressure readings (gauge) taken at the module's back-opening differ by less than 1% between with-canopy and without-canopy cases.

The flow-rate is interesting. First it shows that a wet module allows more air through it than a dry one, both with and without plant roots; and the increase is very substantial, about 50% more. This seems to indicate that water helps to coalesce the "soil" (plant-growing medium) particles, making them larger but also less numerous, thus resulting in perhaps larger pores for air to pass through. This also means wet modules potentially would clean air much better than dry ones.

The difference in air-flow rate between unplanted and planted (with plant roots) cases is much smaller (5 and 10 %), indicating probably that the plant roots play minor roles in creating resistance to the air flow. This would agree with expectation, however, since in terms of individual particles or objects that have a boundary-layer region that tends to inhibit the flow, the roots would offer only a small such region due to their much smaller number in comparison with "soil" particles.

Measurement of back-opening pressure (which essentially is the pressure difference across the module, as discussed above) versus plant type was also taken with the plant-growing medium ("soil") being saturated wet, and the plants fully grown; see Figure 4. The first set of data (hollow symbols) corresponding to "raw" readings shows very large variations in the pressure. However, "soil" bags of two different sizes were used; and the higher pressures were associated with bags weighting about 9.5 kg, whereas the lower pressures with bags weighting about 6 kg. In addition, different baffles were used; these are essentially plastic plates (reinforced with ribs on one side for strength) having multiple holes (circular or triangular) of characteristic dimension 1 – 2 cm for air to go through; these baffles are used to help with keeping the "soil" bags in place, and to even out the air flow. Because the holes are numerous and large (about 90 for circular holes of diameter about 2 cm, and about 780 for triangular holes of side about 1 cm), resistance to air flow by the baffles can safely be taken to be negligible compared to that of the "soil" bag next to them.

On the other hand, Figure 4 also shows the second set of data (filled symbols) of pressure normalized with the weight of the "soil" bag [Pressure / ("Soil"-Bag Weight)] versus plant type. This second data-set indicates very small variations of the normalized pressure among different plant types, here varying only within the narrow range of 3.1 – 3.3 Pa/kg . All this thus corroborates well the conjecture above about the small influence of plant roots and plant canopy on the flow resistance; rather, resistance to air flow is essentially due to the plant-growing medium.

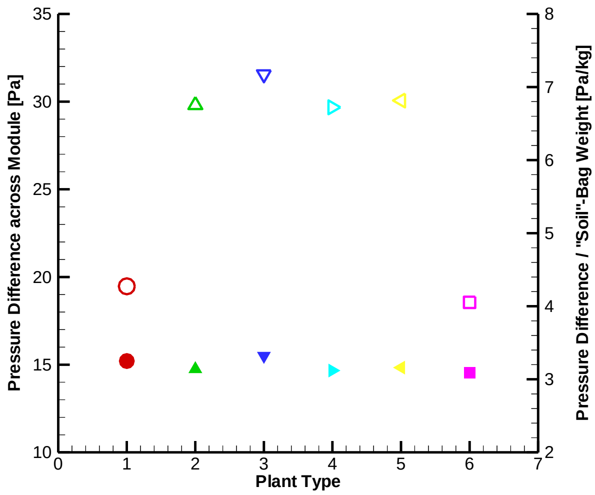

Figure 4. Pressure difference across module for different types of plant. Hollow symbols correspond to "raw" Pressure Difference [Pa], whereas filled symbols correspond to Pressure normalized with the weight of the "soil" bag, i.e. [Pressure Difference / ("Soil"-Bag Weight)] in Pa/kg. Plant types are: 1 Epipremnum aureum; 2 Schefflera amate; 3 Chlorophytum Orchidastrum; 4 Schefflera Arboricola; 5 Ficus lyrata; and 6 Chlorophytum comosum variegatum.

Conclusions

Measurements of air flow through a green-wall module that holds a permeable bag containing a plant-growing medium (replacement for soil) for growing plants have been conducted. Cases of dry and wet (saturated) medium, as well as the medium having plant roots embedded in it and without these roots, have been considered, and the corresponding air-flow rates compared. It's very interesting to see that much more air would pass through the modules, and hence get cleansed, when the modules are wet (here, saturated) than when they are dry. It's conjectured that the main reason for this phenomenon is the medium particles get coalesced by the water, leaving larger pores for air to pass through. Plant roots themselves, on the other hand, play rather minor roles in creating resistance to the air flow.

References

[1] Darlington, A., *The biofiltration of indoor air: Implications for air quality.* Indoor Air, 2000. **10**(1): p. 39-46.

[2] Darlington, A., M.A. Dixon, and C. Pilger, *The use of biofilters to improve indoor air quality: the removal of toluene, TCE, and formaldehyde.* Life support & biosphere science : international journal of earth space, 1998. **5**(1): p. 63-69.

[3] Fernández-Cañero, R., L.P. Urrestarazu, and A. Franco Salas, *Assessment of the cooling potential of an indoor living wall using different substrates in a warm climate.* Indoor and Built Environment, 2012. **21**(5): p. 642-650.

[4] Franco, A., R. Fernández-Cañero, L. Pérez-Urrestarazu, and D.L. Valera, *Wind tunnel analysis of artificial substrates used in active living walls for indoor environment conditioning in Mediterranean buildings.* Building and Environment, 2012. **51**: p. 370-378.

[5] Kontoleon, K.J. and E.A. Eumorfopoulou, *The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone.* Building and Environment, 2010. **45**(5): p. 1287-1303.

[6] Munson, B.R., A.P. Rothmayer, T.H. Okiishi, and W.W. Huebsch, *Fundamentals of Fluid Mechanics*. 7th ed. 2013: Wiley.

[7] Pérez, G., L. Rincón, A. Vila, J.M. González, and L.F. Cabeza, *Green vertical systems for buildings as passive systems for energy savings.* Applied Energy, 2011. **88**(12): p. 4854-4859.

[8] Perini, K., M. Ottelé, A.L.A. Fraaij, E.M. Haas, and R. Raiteri, *Vertical greening systems and the effect on air flow and temperature on the building envelope.* Building and Environment, 2011. **46**(11): p. 2287-2294.

[9] Torpy, F.R., M. Zavattaro, P.J. Irga, and M.D. Burchett, *Assessing the air quality remediation capacity of the JUNGLEFY breathing wall - Modular plant wall system.*, in *Research Report*. 2015, School of Life Sciences, Faculty of Science, University of Technology Sydney.