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The potential for vertical gardens as evaporative coolers: An adaptation of the 'Penman Monteith Equation'

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ABSTRACT

This research paper investigates the use of vertical gardens as evaporative coolers. Vertical gardens play a key role in tackling the increasing challenges cities face, due to a rapidly growing urban environment with associated reductions in vegetation and an increase in the urban heat island effect. This paper aims to develop a mathematical model based on the FAO-56 Penman Monteith Equation that quantifies the effects of vertical gardens for evaporative cooling. The theoretical results are then compared with empirical findings for the experimental setup undertaken by Davis & Ramirez [1], which involved passing air behind the vertical garden (between the substrate and the surface). Correlation is observed when the computed value is at the lowest humidity (35%) of the three test runs (35%, 40%, and 45%). This either indicates that the vertical garden performs better than predicted by the mathematical model, or the relative humidity at the time when the measurements were made was in the region of 35% instead of the predicted 40%. This research indicates the potential for the FAO-56 Penman Monteith Equation to be integrated into a future design tool that facilitates the application of vertical gardens as evaporative coolers in building designs.

1. Introduction

The rapid growth of cities around the world is coupled with reductions in vegetation and an increase in the urban heat island effect [2]. The many benefits of plants in urban environments include air purification [3], reduced stress levels [4] and increased productivity and well-being [5]. Additionally, Perini [6] point out how ever-growing rates of urbanization go hand-in-hand with the need to implement green spaces in buildings.

Santamouris [7] explains how the urban heat island phenomenon is caused by rising trends of urbanisation and industrialisation, where the heat increase in urban areas can be up to 15 °C when compared to non-urbanised surroundings. Inevitably, this is coupled with an increase in electricity demand for cooling buildings [7]. Each degree of temperature increase during peak cooling hours correlates with a subsequent increase in the electricity used in cooling buildings. Urban vegetation can play a clear role in mitigating this, where greenery helps to reduce heat transfer between a building and its environment, as well as providing a form of shade that absorbs solar radiation [8]. More specifically, vertical gardens made up from substrate panels are able to mitigate building façade surface temperature fluctuations when installed, as well as cooling ambient temperatures up to 0.6 m away from the garden surface, which reduces the air intake temperatures and hence cooling loads for air-conditioning [9].

This paper begins by exploring the role of vertical gardens, first as passive air conditioning systems and second as evaporative coolers. It then goes on to look at the need for a mathematical model, proposing an equation to be used as a design tool, based on the FAO-56 Penman Monteith Equation. Finally, the theoretical results for the design tool are compared to the experimental results from research by Davis & Ramirez [1]. The results are found to be promising for further research, where in-situ measurements of relative humidity are needed in order to better determine the level of accuracy of the proposed mathematical model.

2. The role of vertical gardens

Vertical gardens (also referred to as green walls, green façades and living walls) are an important factor in improving urban environments [10]. Loh [11] defines vertical gardens as:

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- Trellis systems: where plants are rooted in containers and grown up trellises.
- Felt systems: where plants are rooted in pockets in a felt substrate, which is in turn attached to a waterproof backing and held up by a supporting structure.
- Panel systems: where panels with plants and substrate are pre-grown, after which they are brought to site and fitted onto a supporting structure.

Ottelé [12] and Peréz [13] also include climbing plants that are rooted in the ground and grown up the wall of a building. In the case of this paper only the panel system is examined, where it is connected to a ventilation unit to act as an evaporative cooler.

2.1. Vertical gardens as passive air conditioning systems

Overall, research shows that the shadow created by the plants of vertical gardens, coupled with the cooling effects of evapotranspiration, has a positive effect in reducing the energy consumption normally dedicated to cooling of a building [14]. This is expanded on by Pérez [15]. They identify four main mechanisms in the use of vertical gardens as cooling systems:

1) Shadow produced by the vegetation.
2) Protection against solar radiation provided by the vegetation and substrate.
3) Evaporative cooling by evapotranspiration.
4) The reduction in the influence of wind on the building due to the protective barrier of the vertical garden.

Ottelé [12] further reinforces this by arguing that the climatic conditions at the face of a typical bare façade can be linked to an arid or alpine climate, due to the large difference between hot temperatures during the day and cold temperatures during the night. However, a dense vertical green layer on the façade has an insulating effect that reduces this significantly. Additionally, plants retain water on the surfaces of their leaves longer than building facades, which acts as an additional insolation buffer. This together with the process of transpiration leads to a more pleasant urban climate.

Stec [15] takes the concept of plants as cooling and bioclimatic shading systems a step further in his research into double skin façades. He introduces the use of the 'Penman Monteith Equation' as a means of modelling the latent heat contribution in reducing a building's sensible heat gains. Stec simplified the 'Penman Monteith Equation' primarily to a coefficient of solar radiation, arguing that the effects of air velocity, ambient temperature, and relative humidity were negligible in comparison.

2.2. Vertical gardens as evaporative coolers

An active vertical garden, where it is connected to a building's mechanical air conditioning system to act as an evaporative cooler, has to date received little attention. In the 1980's Wolverton [3] put forward the possibilities of connecting pot plants to an activated carbon filter and ventilation system for air purification in urban households. This was later further investigated by Wood [16]. Darlington [17] then showed that the connection of a vertical garden to the University of Guelph's HVAC system, significantly reduced a number of certain Volatile Organic Compounds (VOC's) from the air.

More recently Davis & Ramirez [1] carried out experimental work with a modified vertical garden module, where they activated it to climatise incoming air using three methods (shown in Fig. 1):

– **Method 1**: By passing a controlled flow of air over the foliage of the vertical garden module encased in a glass chamber. The air was to be cooled by the plant transpiration much in the same manner as explored by Stec [16].
– **Method 2**: By passing air behind the vertical garden, in the space between the substrate and the surface onto which the garden was attached. In this mechanism the air was cooled and humidified through its contact with the humid substrate.
– **Method 3**: By sucking air through the vertical garden, in a similar manner to Darlington's wall [17].

Overall the results were found to be promising. The research suggests that the most effective manners by which incoming air is climatised were either through Method 2 (by passing air behind the vertical garden), and by Method 3 (drawing air through the substrate) but in the absence of a glass fronting [1]. Using the findings from Davis & Ramirez [1], the authors have developed a mathematical model to compare against the experimental results from Method 2 – the reasons for this choice are briefly discussed in Section 3.

3. The case for a mathematical model

In order to incorporate vertical greenery as active, evaporative coolers into mechanical engineering and HVAC design, it is necessary to have a mathematical model that serves as a design tool for engineers. Stec [15] showed that the 'Penman Monteith Equation' served as an accurate tool in predicting the latent heat release from plants in a vertical façade. For this reason this paper uses the Penman Monteith Equation as a starting point, from which the authors set out to develop a mathematical model that could be used to develop a design tool in the future.

In the case of Stec [15] the main function of the greenery was to convert solar radiation to latent heat. Stec [15] simplified the Penman Monteith Equation mainly to a coefficient of solar radiation, arguing that the effects of air velocity, ambient temperature and relative humidity were negligible in comparison. An overview of using the Penman Monteith Equation for the three cases studied by Davis & Ramirez [1] is given below:

– **Method 1**: By passing air in controlled flow over the foliage of the vertical garden module encased in a glass chamber: in this case the existing Penman Monteith Equation is justified because the plants receive solar radiation, and airflow is passed over the foliage at a given temperature and relative humidity.
– **Method 2**: By passing air behind the vertical garden, in the space between the substrate and the surface onto which the garden was attached: in this case the airflow is shielded from solar radiation, and therefore a simplified approach to the Penman Monteith Equation is required where influences from solar radiation are removed.
– **Method 3**: By sucking air through the vertical garden: in this case the evaporative cooling is carried out much in the same way as a swamp (or sump) cooler, and so a different mathematical model is needed that is distinct to the Penman Monteith Equation.

Davis & Ramirez [1] found Method 1 to not be very effective, due to the air being heated in the glass chamber. Therefore for this paper the authors have focused on Method 2.

3.1. An adaptation of the FAO-56 Penman Monteith Equation

Theoretical research into the evaporation rates of plants typically uses the Penman–Monteith Equation. This formula for

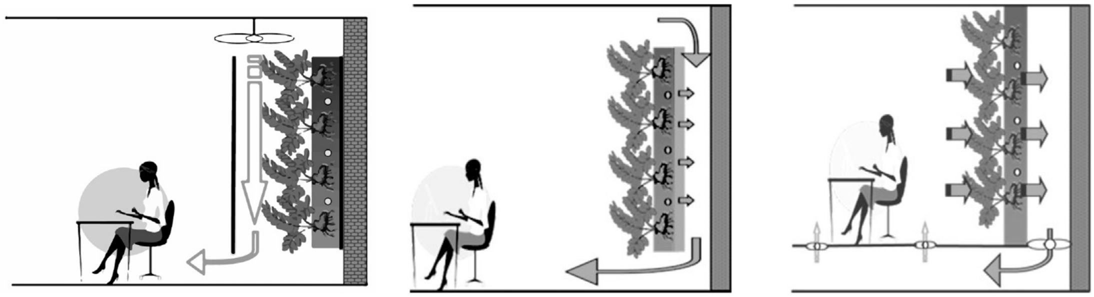

Fig. 1. Possible ways a vertical garden can be activated for air conditioning [1].

computing water evaporation from vegetated surfaces was developed by John Monteith in his seminal paper [18], where he built on work by Howard Penman (as seen in Ref. [18]). Subsequent development of the formula by various researchers and agencies has led to a number of simplified versions of the equation. Amongst these is the standardised version of the Penman–Monteith Equation from the United Nations (UN) Food and Agriculture Organisation (FAO), known as the FAO-56 Penman–Monteith Equation. In this case the original Penman–Monteith Equation was standardised by Allen et al. [19] to meet the requirements of the FAO. Among other assumptions, it was assumed that the vegetation consisted of clipped grass of height 0.12 m with a known bulk surface resistance. The evaporation for various crop types could then be determined by multiplying the standardised equation (for the theoretical clipped grass) by the appropriate crop coefficient (for the actual crop being studied).

The FAO-56 Penman–Monteith Equation is given as (Based on [19]):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)U_2(e^0 - e_a)}{\Delta + \gamma(1 + 0.34U)} \quad \left[\text{mm day}^{-1}\right] \tag{1}$$

where:

ET_0 = reference crop evapotranspiration [mm day^{-1}]
Δ = slope of the saturated vapour pressure curve [kPa $^\circ C^{-1}$]
R_n = solar radiation [MJ $m^{-2}day^{-1}$]
G = sensible heat flux into substrate [MJ m^{-2} day^{-1}]
γ = psychometric constant [kPa $^\circ C^{-1}$]
T = mean air temperature [°C]
U_2 = wind speed 2 m above the ground surface [m s^{-1}]
e^0 = mean saturated vapour pressure [kPa]
e_a = mean daily ambient vapour pressure [kPa]

The FAO-56 Penman–Monteith Equation has been tested in practise by Evett and Howell [20] for crops in the open air and found to perform satisfactory. Research has also been carried out by Stanghellini & Van Meurs [21] and Stec [15], where the Penman–Monteith Equation was successfully applied to vegetation in a greenhouse and a double-skin façade respectively. Hence, the FAO-56 Penman–Monteith Equation has been chosen to study the potential for vertical gardens functioning as evaporative coolers. This is similar to the research conducted by Davis & Ramirez [1] discussed in Section 2.2. When air flows in the air chamber behind the garden between the substrate and backing wall, as seen in the Davis & Ramirez [1] Experiment (Method 2), it is possible to estimate the evaporation from the substrate. This in return allows the theoretical effect of cooling the airflow through evaporation to be calculated.

From an evaluation of the experimental setup of Davis & Ramirez [1], in addition to the existing research discussed above, certain modifications have been proposed to the FAO-56 Penman–Monteith Equation, which are discussed below.

3.1.1. Adaptation of wind speed values

In the FAO-56 Penman Monteith Equation (1) U_2 refers to the wind speed as measured 2 m above the crop surface [19], however in the case of Davis & Ramirez [1] the airflow is considered to be uniform in the air chamber behind the garden between the substrate and backing wall. Therefore, the following adjustment is proposed:

In the FAO-56 Penman–Monteith Equation the wind speed is related to the aerodynamic resistance, r_a, where [19]:

$$r_a = \frac{ln\left(\frac{z_m - d}{z_{om}}\right) ln\left(\frac{z_h - d}{z_{oh}}\right)}{k^2 U_z} \tag{2}$$

where:

z_m = height of wind measurements [m]
z_h = height of humidity measurements [m]
d = xero plane displacement height [m]
z_{om} = roughness level governing momentum transfer [m]
z_{oh} = roughness level governing transfer of heat and vapour [m]
k = von Karmen's constant = 0.41 [–]
U_z = wind velocity at height z m [m s^{-1}]

With:

$d = {}^2/_3$ crop height $= {}^2/_3$ h
z_{om} = 0.123 crop height = 0.123 h
$z_{oh} = 0.1\ z_{om}$

When wind and humidity measurements are made at 2 m above crop surface with a constant height of 0.12 m (as in the FAO-56 Penman–Monteith Equation) [19]:

$$r_a = \frac{ln\left(\frac{2-\frac{2}{3}\times 0.12}{0.123\times 0.12}\right) ln\left(\frac{2-\frac{2}{3}\times 0.12}{0.1\times 0.123\times 0.12}\right)}{0.41^2 U_2} = \frac{208}{U_2} \tag{3}$$

where:

U_2 = wind speed at 2 m [m s^{-1}]

When wind and humidity measurements are made at 0 m above crop surface with a constant height of 0.12 m:

$$r_a = \frac{ln\left(\frac{h-\frac{2}{3}h}{0.123h}\right) ln\left(\frac{h-\frac{2}{3}h}{0.1(0.123h)}\right)}{k^2 U_0}$$

$$r_a = \frac{ln\left(\frac{\frac{1}{3}\times 0.12}{0.123\times 0.12}\right) ln\left(\frac{\frac{1}{3}\times 0.12}{0.1\times 0.123\times 0.12}\right)}{0.41^2 U_0} = \frac{19.6}{U_0}$$

where:

U_0 = wind speed at 0 m [m s^{-1}]

If we then compare U_2 with U_0:

$$\frac{208}{U_2} = 10.5\left(\frac{19.6}{U_0}\right)$$

And as such the assumption is made that, for the wind speed at the surface of the substrate, a factor of 10.5 has to be added, hence:

$$U_2 = 10.5U_0 \quad (4)$$

where:

U_2 = wind speed 2 m above the ground surface [m s^{-1}].
U_0 = wind speed 0 m above the ground surface [m s^{-1}].

Therefore, the Penman–Monteith FAO-56 to predict evaporation behind the vertical garden from the substrate becomes:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)(10.5U_0)(e^0 - e_a)}{\Delta + \gamma(1 + 0.34(10.5U_0))} \left[\text{mm day}^{-1}\right] \quad (5)$$

Furthermore, by channelling the air between the substrate and the backing wall it is protected from solar radiation gain, and hence the FAO-56 Penman–Monteith Equation can be further simplified to:

$$ET_0 = \frac{\gamma\frac{900}{T+273}(10.5U_0)(e_s - e_a)}{\Delta + \gamma(1 + 0.34(10.5U_0))} \left[\text{mm day}^{-1}\right] \quad (6)$$

3.1.2. Adjusting the units

For the purpose of calculating the climatisation aspects of vertical gardens it is also necessary to convert the units of ET_0 from [mm day^{-1}] to [mm s^{-1}]. There are 86,400 s in a 24 h day, and thus:

$$ET_0 = (1/86400) \times \frac{\gamma\frac{900}{T+273}(10.5U_0)(e_s - e_a)}{\Delta + \gamma(1 + 0.34(10.5U_0))} \times \left[\text{mm s}^{-1}\right] \text{ o } \left[\text{ltr s}^{-1}\text{ m}^{-2}\right] \text{ or } \left[\text{ltr s}^{-1}\text{ m}^{-2}\right] \text{ or } \left[\text{kg s}^{-1}\text{ m}^{-2}\right] \quad (7)$$

where this final change in units is:

- 1 m^3 of water = 1000 L.
- 1 m^2 by 1 mm high of water = 1 L.
- 1 mm of evaporation = 1 L per m^2 (Fig. 2)
- 1 L of water = 1 kg.

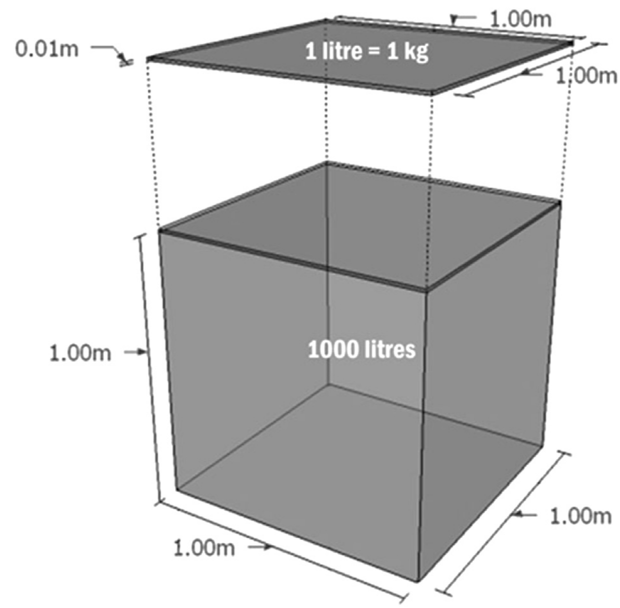

Fig. 2. The unit change [mm s^{-1}] to [ltr m^{-2} s^{-2}] or [kg s^{-1} m^{-2}].

3.1.3. Accounting for the increased evaporation of the saturated substrate surface

Finally, in the case of air flowing between the substrate and the backing wall, a saturated substrate surface has been found to evaporate approximately 1.15 more water than the reference crop of clipped grass transpires [19]. Hence, the final equation is:

$$ET_{substrate} = (1.15/86400) \times \frac{\gamma\left(\frac{900}{T+273}\right)(10.5U_0)(e_s - e_a)}{\Delta + \gamma(1 + 0.34(10.5U_0))} \times \left[\text{mm s}^{-1}\right] \text{ or } \left[\text{ltr s}^{-1}\text{ m}^{-2}\right] \text{ or } \left[\text{ltr s}^{-1}\text{ m}^{-2}\right] \text{ or } \left[\text{kg s}^{-1}\text{ m}^{-2}\right] \quad (8)$$

The change in temperature can then be deduced via an equation of energy equilibrium:

$$\Delta T = \frac{ET_{substrato} \times \lambda}{Q \times \rho \times c} \quad (9)$$

where:

ΔT = decrease in temperature [°C]
$ET_{substrate}$ = the evaporation from the substrate at the back of the vertical garden [kg s^{-1}]
λ = the latent heat of water = 2.45 × 10^6 [J kg^{-1}]
Q = the mass air flow rate of the air behind the vertical garden [m^3 s^{-1}]
ρ = air density = 1.2 [kg m^{-3}]
C = the specific heat of air = 1000 [J kg^{-1} °C^{-1}]

3.1.4. Accounting for the adiabatic air-cooling capacity decrease over given wall length

A further factor that needs to be taken into account is that when the hot, dry air comes into the gap behind the vertical garden, it will be cooled and humidified as it travels down the depth of the back of the green wall. An increase in humidity, and subsequent drop in temperature for the air passing over one section, leads to a decrease in water vapour that can be absorbed as the air passes over the next section. This means that with the air becoming cooler and more humid as it travels down the depth of the gap, the adiabatic air-cooling capacity decreases over the length of the wall. This is distinct from the traditional use of the FAO-56 Penman–Monteith for crop transpiration, where the crop surface is essentially treated as one large leaf that transpires uniformly on a horizontal plane [19]. To account for this decrease in air-cooling capacity, the wall is simply divided into 10 separate sections. The increase in relative humidity and decrease in temperature of the air passing over the first section down the back of the green wall is then calculated, and the result is then used as the input for the air passing over the subsequent wall section. This process is repeated until all 10 sections are assessed.

3.1.5. Assumptions to the FAO-56 Penman–Monteith Equation methodology

Regarding the validity of the application of the FAO-56 Penman–Monteith Equation it was also assumed in the experimental work of Davis & Ramirez [1] that:

- There was mass conservation of the airflow that flows behind the garden and exits the ventilation system, with negligible additions or losses through the substrate.
- The airflow was turbulent and as such the whole volume of air flowing behind the vertical garden is in contact with the substrate surface.

4. Results and discussion

The next stage of this study is to compare the theoretical mathematical model put forward, with the results of the experimental work shown in Fig. 3 of Davis & Ramirez [1]. The vertical garden used by Davis & Ramirez [1] consisted of a 1.2 m high, 0.9 m wide garden, with an airspace between the substrate and garden casing of 0.05 m. Measurements of the air velocity and dry bulb temperature were then taken over a matrix at the top, middle and bottom of the garden in the air chamber behind the substrate. In addition measurements were taken of the air coming out of the ventilators at the bottom of the experimental module.

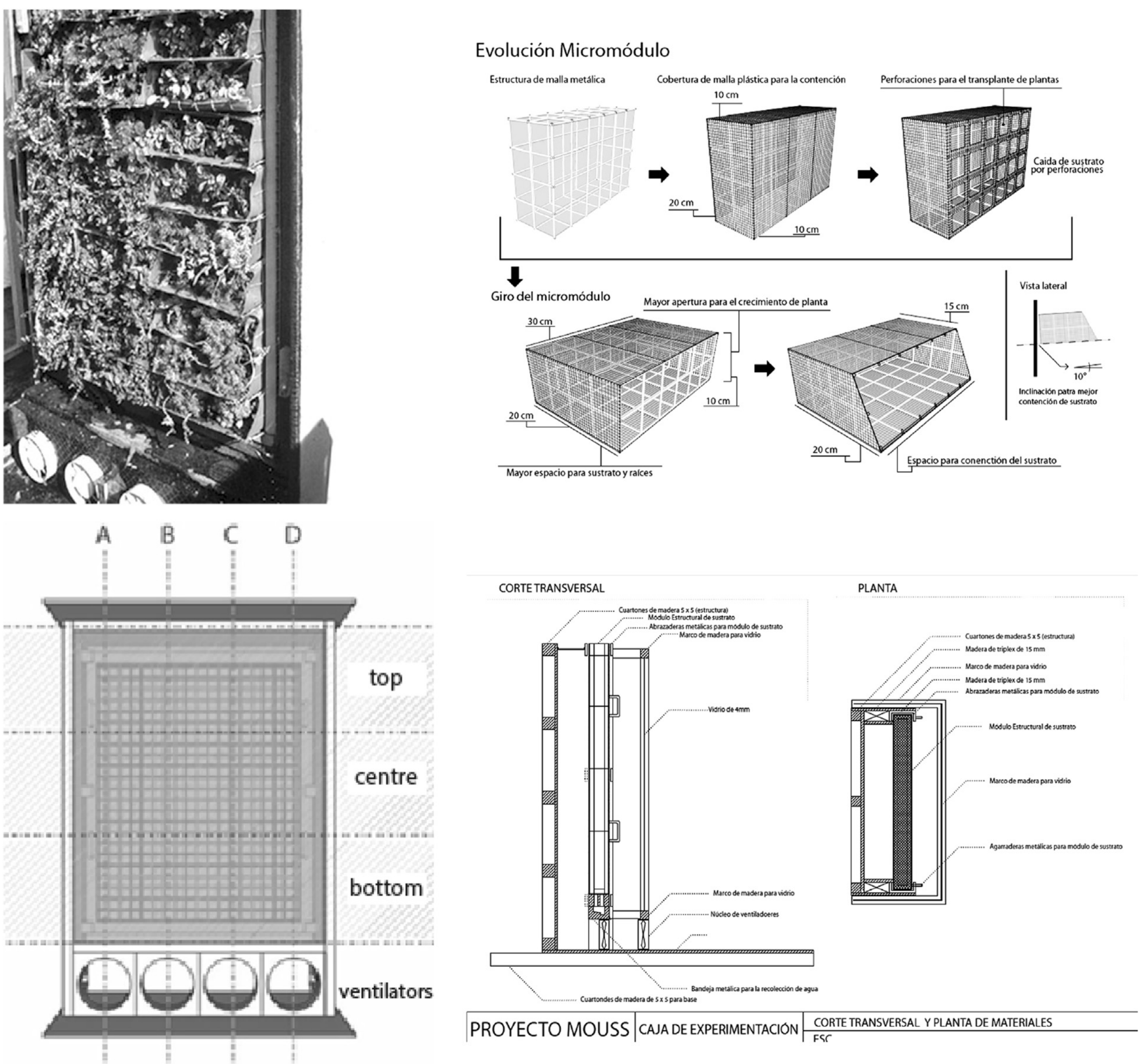

Fig. 3. Vertical garden used by Davis & Ramirez [1].

Table 1
Temperature measurements for airflow behind the substrate (adapted from [1]).

		Top (°C)	Centre (°C)	Bottom (°C)	Fans (°C)
A	1	23,35	22,13	21,35	21,35
	2	23,70	22,29	20,63	21,85
	P	23,53	22,21	20,99	21,6
B	1	22,50	21,71	21,21	20,36
	2	23,10	21,51	20,69	20,48
	P	22,80	21,61	20,95	20,42
C	1	21,23	20,51	19,83	20,29
	2	21,46	20,42	19,81	20,38
	P	21,345	20,465	19,82	20,335
D	1	21,38	20,53	20,38	20,78
	2	21,57	21,01	20,43	20,53
	P	21,475	20,77	20,405	20,66
Averages		22,29	21,26	20,54	20,75

Date: 25/11/2011, Time: 13h15, Weather: Sunny.

The results from the experimental work of Davis & Ramirez [1] where the air was channelled behind the substrate are shown in Table 1 and Table 2. These tables show the temperature and air velocity measurements for the points of the matrix at the top, middle and bottom of the garden in the air chamber behind the substrate and garden casing, and in addition the air leaving the ventilators at the bottom of the experimental module. Fig. 3 above depicts a vertical garden setup. The vertical garden illustration is broken up into vertical segments A, B, C, D and horizontal segments top, centre, bottom. Measurements are shown in Table 1 below. The measurements labelled “Fans” are those taken from the ventilators.

Based on these results the following initial values were adopted for Eq. (8) for the air before it flowed behind the substrate:

$$T = 22.29[^\circ C]$$

$$U_0 = 3.50\left[\mathrm{ms}^{-1}\right]$$

The value for U_0 was also used in order to calculate the mass flow rate for Eq. (9), where:

$$Q = U_0 \times b \times w \tag{10}$$

and where:

U_0 = air velocity at the substrate surface = 3.50 [m s^{-1}]
b = breadth of gap behind the garden substrate = 0.05 [m]
w = width of garden = 0.9 [m]

As such the mass flow rate for the air flowing behind the garden substrate can be calculated as:

$$Q = 0.189\left[\mathrm{m}^3\mathrm{s}^{-1}\right]$$

In the case of the FAO-56 Penman–Monteith Equation it is necessary to also know the relative humidity at the time of experiment. Unfortunately, this was not explicitly measured. However, the humidity can be estimated using data from the Anuario 2011 of the Instituto Nacional de Meterología e Hidrología of Ecuador [22]. For this paper, the relative humidity measurements for the month and year of experimentation were examined from the nearest meteorological station to the experimentation site. The experimentation was carried out at a hot time of the day, when solar irradiation levels would have been high. Additionally, the experimental notes in Table 1 states that the weather was sunny. It is therefore argued to be reasonable to assume that the relative humidity levels were at the lower end of their daily fluctuations, and as such the average minimum value for relative humidity for the November 2011 (the month when the experiment of Davis & Ramirez [1] was carried out) could be adopted, which was found to be 40%

Based on the above, the results for the cooling predicted from the modified FAO-56 Penman–Monteith Equation (8) and subsequent change in temperature (9), are shown for relative humidities of 35%, 40%, and 45% respectively for the air velocities and initial air temperatures measured in Davis & Ramirez's [1] experiment in Fig. 4.

These results are then plotted with the experimental results from Davis & Ramirez [1] in Fig. 5 below.

By comparing the experimental and computed results in Fig. 5, it can clearly be seen that the results computed for the lowest value of relative humidity of 35% seem to be closest to those measured in practise by Davis & Ramirez [1]. This indicates that either:

a) The vertical garden performs superiorly to that predicted by the mathematical model.

Table 2
Air velocity measurements for airflow behind the substrate (adapted from Ref. [1]).

	TOP (m/s)	Fans (m/s)
A	3.30	4.55
B	3.75	4.58
C	3.40	4.60
D	3.55	4.50
Avrg.	3.50	4.56

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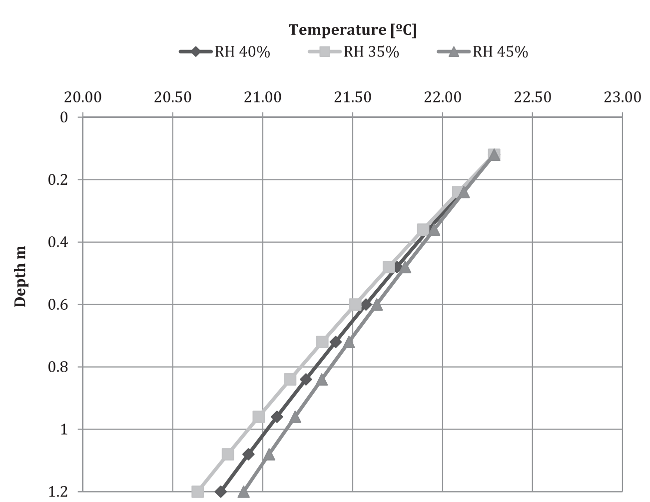

Fig. 4. Cooling predicted from the modified FAO-56 Penman–Monteith Equation.

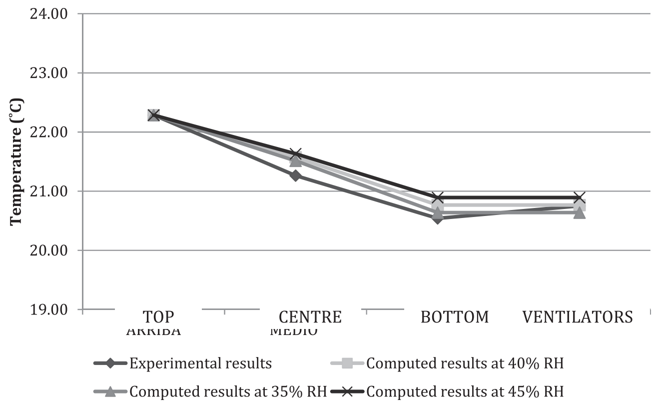

Fig. 5. Comparison of experimental results with cooling predicted.

b) The relative humidity at the time when the measurements were made was in the region of 35%.

In either scenario, the results are promising, and indicate the potential for vertical gardens as an evaporative coolers, using the modified FAO-56 Penman–Monteith Equation to predict the cooling power. However, it is necessary to carry out further research where relative humidity measurements are made, in addition to temperature and air velocity, for this to be quantified in a more satisfactory manner.

5. Conclusion and further research

This research paper sought to investigate the use of vertical gardens as evaporative coolers. The aim was to incorporate vertical gardens as evaporative coolers into building design, in an effort to tackle the increasing challenges posed by rapidly growing cities. These challenges include a reduction in vegetation and an increase in the urban heat island effect. In this paper the existing FAO-56 Penman–Monteith Equation as given by Allen [19] was used as a baseline for developing a mathematical model for vertical gardens as evaporative coolers. The equation was modified such that it could be used to predict the theoretical evaporation rate from air flowing in the space between the substrate and the surface onto which a vertical garden is attached. The mathematical model was then run with input data from Davis & Ramirez [1] and weather data for Quito. The results indicated a promising correlation between the mathematical model and empirical experiment, but suggested that either the relative humidity level was lower than estimated, or that the vertical garden performed in a superior manner to that predicted by the mathematical model. It is therefore recommended that additional work is carried out to explore the benefits of active vertical gardens as evaporative coolers. This includes further research where relative humidity measurements are made (in addition to temperature and air velocity) in order to accurately compare and quantify the results of the mathematical model. Nevertheless, the findings demonstrate the potential for the modified FAO-56 Penman Monteith Equation to be integrated into a future design tool, which could facilitate the application of vertical gardens as evaporative coolers in building design.

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