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Vertical gardens as swamp coolers

M.J.M. Davis[a,b,]*, F, Ramírez[a], A.L. Vallejo[a]

[a]*Pontificia Universidad Católica del Ecuador, Av. 12 de Octubre 1076 y Roca, Quito593, Ecuador*
[b,]*Evolution Engineering Design and Energy Systems,5 Silver Terrace, EX4 4JE, UK*

Abstract

This paper explores the potential of a vertical garden to function as a swamp cooler, passing an airflow through the substrate, in much the same way as in a direct evaporative cooler. The 2011 ASHRAE handbook [1] provides guidance on the use of evaporative coolers. They are presented as a low energy contender for air conditioning systems in hot, dry climates. The most basic and direct evaporative coolers (a.k.a. swamp coolers) work by converting sensible heat in the air into latent heat, by passing air through a saturated pad (i.e. the energy required to evaporate water into the air). The concept presented here is that a vertical garden can act as a swamp cooler. This concept is based on the research by Davis & Ramirez [2] on vertical gardens. Davis & Ramirez [2] found that a vertical garden had the potential to act as a swamp cooler. However, there were complications in quantifying the effectiveness of the cooling, due to a suspected pre-heating of the incoming airflow because of glass fronting to the vertical garden. This paper sets out to build on Davis & Ramirez's work, where the experiment is replicated without the glass fronting and where improved measurements of temperatures and relative humidity levels are taken. Thus, a more reliable efficiency is determined for a vertical garden as a swamp cooler.

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Keywords: Sustainable energy; Vertical gardens; Direct evaporative cooling; Swamp cooler; Substrate

* Corresponding author. Tel.: +593-981-869-424/ +44-139-258-1579.
E-mail address: davismaks@cantab.net

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1. Introduction

Cities all over the world are growing, leading to an increase in the phenomenon known as the urban heat island effect, whilst at the same time urban vegetation is in decline [3]. Urban vegetation has many benefits, including air purification [4], a reduction in stress levels [5], increased productivity and a heightened sense of well-being [6]. Santamouris [7] tells us the heat increase in urban areas can be up to 15ºC when compared to non-urbanized surroundings. He adds how this will often be coupled with an increase in electricity demand for cooling the interiors of urban buildings to comfortable temperatures. For every degree of temperature increase in peak cooling hours there is a subsequent increase in electricity used by the HVAC system [7]. Urban vegetation can mitigate this however, by reducing the heat transfer between a building and its surrounding environment, in addition to providing solar shading that absorbs radiation from the sun [8].

Nomenclature

b	= breadth gap behind the substrate [m]
ε	= effectiveness of the cooler [-]
T_{db}	= temperature of the incoming air before passing through the pad or vertical garden substrate [°C]
T_{cooled}	= Temperature of the outgoing air after passing through the pad or vertical garden substrate [°C]
T_{wb}	= wet bulb temperature of the air [°C]
RH_{db}	= Relative humidity of the incoming air before passing through the vertical garden substrate [%]
V	= air velocity at the inlet [m/s]
w	= width of vertical garden [m]

1.1. Vertical gardens as passive air conditioning systems

The use of vertical greenery as a cooling system for buildings is a fairly new area of research [9]. Overall it has been shown that the building's energy consumption dedicated to cooling is reduced with vertical greenery being incorporated into the building envelope, due to the cooling effects of evapotranspiration and solar shading [10]. Ottelé [11] shows how a dense vertical layer of greenery on the building façade acts as an insulator, due to a stagnant layer of air forming between the foliage and the façade. Additionally he shows how plant leaves retain water on their surfaces longer than most building materials, providing an additional thermal buffer. This is then taken a step further by Stec [12], where he studies the use of plants as bioshading systems in double skin facades. He shows how the plants' latent heat contribution greatly reduces the sensible heat gains the building would otherwise receive.

Perez et al. [13] go on to summarize four manners in which vertical gardens act as passive cooling systems.

- Shadow produced by the vegetation.
- Protection against solar radiation provided by the vegetation and substrate.
- Evaporative cooling by evapotranspiration.
- A reduction in heat losses related to wind acting on the building, due to the protective barrier of the vertical garden.

1.2. Vertical gardens as evaporative coolers

An active vertical garden is defined for this research as a vertical garden that is connected to a building´s mechanical air conditioning system in order to act as an evaporative cooler.

In the 1980's Wolverton [4] put forward the possibility of connecting pot plants to an activated carbon filter and ventilation system for air purification in urban households. This was further investigated by Wood [14] and

Darlington, Dat and Dixon [15]. In the research of Darlington, Dat and Dixon [15] a large scale vertical garden, spanning a number of building floors, was connected in series to the University of Guelph's HVAC system for biofiltration. It was shown to significantly reduce certain Volatile Organic Compounds (VOC's) from the air [15].

More recently Davis & Ramirez [2] carried out experimental work with a modified vertical garden module, where they activated it to climatise incoming air in one of three manners (Figure 1):

- **Method 1:** By passing air in a controlled flow over the foliage of the vertical garden module encased in a glass chamber, where the air was to be cooled by the plant transpiration.
- **Method 2:** By passing air behind the vertical garden, in the space between the substrate and the surface onto which the garden was attached. This mechanism was to have the air-cooled and humidified through its contact with the humid substrate.
- **Method 3:** By sucking air through the vertical garden, where the air was to be cooled in a manner similar to a traditional swamp cooler.

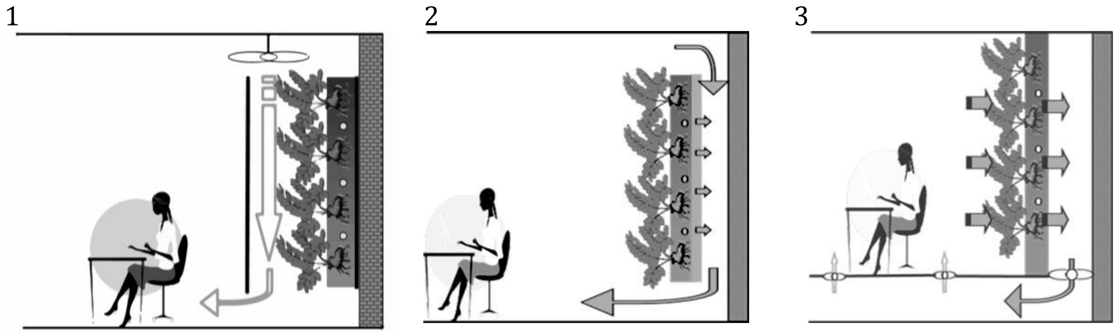

Figure 1: The three possible ways a vertical garden could be activated for air conditioning (adapted from Davis & Ramirez [2]).

Their research suggested that the most effective manners were using Method 2 (by passing air behind the vertical garden), and hypothetically Method 3 (by drawing air through the substrate). In the case of Method 3, it seemed that when the air was drawn into the glass chamber, it was pre-heated before passing through the substrate (Figure 2 and Figure 3). The aim of this paper is to quantify the efficiency of Method 3 with a further degree of certainty, by repeating the experimentation of Davis & Ramirez [2] but with the absence of a glass fronting.

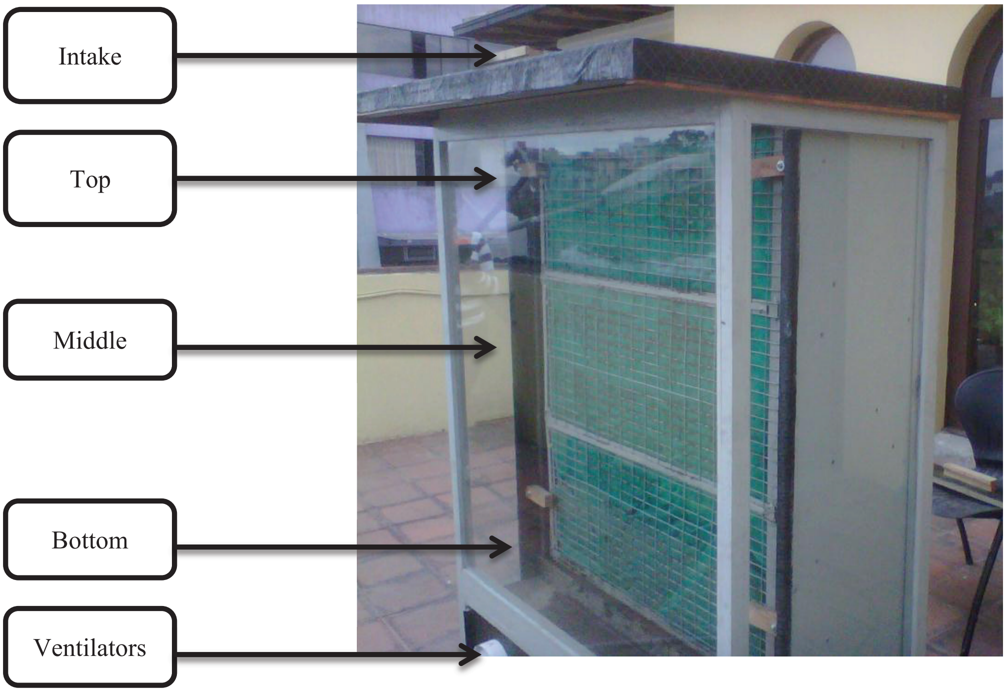

Figure 2: Position of measurements when air flowed from the intake first into the glass chamber, then out from the ventilators after having passed through the substrate (adapted from Davis & Ramirez [2])

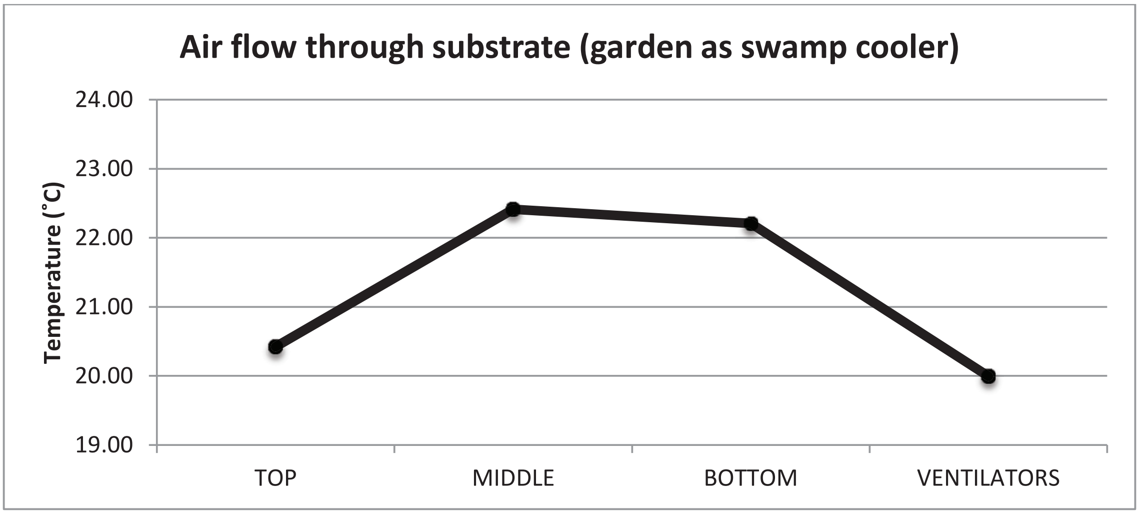

Figure 3: Temperature measurements of airflow at the garden intake, in the glass chamber and out from the ventilators after having passed through the substrate (adapted from Davis & Ramirez [2]).

1.3. Airflow through the substrate and the vertical garden as a swamp cooler

In this case the air is cooled by the latent heat released by the saturated substrate as the air passes through it. Guidance on the use of evaporative coolers can be found in the 2011 ASHRAE Handbook, where evaporative cooling is presented as a low energy contender for air conditioning systems in hot, dry climates [1]. The most basic and direct evaporative coolers (a.k.a. swamp coolers) work by converting sensible heat in the air to latent heat (i.e. the energy required to evaporate water into the air) by passing the air through a saturated pad. In the case of this research, the saturated substrate of the vertical garden acts in a similar manner to the saturated pad of an evaporative cooler. The Handbook explains how the incoming air will have a dry and wet bulb temperature. In order to completely bring air from its dry to its wet bulb temperature, the adiabatic system would need to be 100% effective. However, this is not the case as swamp coolers depend on the rate of air flow through the saturated pad, ambient climatic conditions, as well as the physical properties of the pad that determine its ability to release water (such as porosity, thickness and level of saturation). In general the cooling from evaporative coolers is given by:

$$T_{cooled} = T_{db} - \varepsilon(T_{db} - T_{wb}) \quad (1)$$

Where:
T_{db} = temperature of the incoming air before passing through the pad [°C]
T_{wb} = wet bulb temperature of the air [°C]
T_{cooled} = Temperature of the outgoing air after passing through the pad [°C]
ε = effectiveness of the cooler [-]
[1]

In this case it is air flow rate, the ambient climatic conditions and the physical properties of the substrate that determine the effectiveness of the vertical garden as an evaporative cooler. It is assumed here that:

- All evaporative cooling takes place as the air passes through the saturated substrate.
- The garden is effectively sealed and no airflow is possible other than that passing through the substrate.

Equation (1) can then be rearranged to give:

$$\varepsilon = \frac{(T_{db} - T_{cooled})}{(T_{db} - T_{wb})} \quad (2)$$

2. Methodology

The vertical garden for this research was similar to that used by Davis & Ramirez [2], except this garden did not have any glass fronting incorporated. This avoided the air being preheated before passing through the garden substrate. The dimensions of the vertical garden and supporting module are shown in Figure 4.

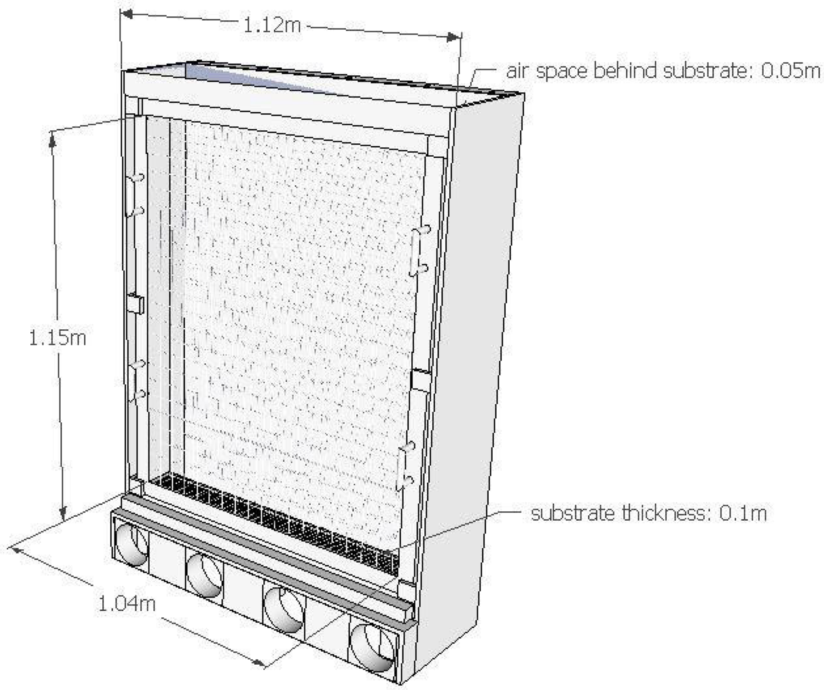

Figure 4: Vertical garden and supporting module dimensions.

The vertical garden module was made from a galvanized steel frame and mesh. A fine plastic mesh lining was then used to hold the substrate inside the module. This allowed air to flow freely, whilst at the same time ensuring that the substrate was held firm. The substrate was made up from a mix of sphagnum, peat and coconut chip. The vegetation was then planted in pockets cut into the fine mesh. Finally, the vertical garden module was placed in a waterproof casing, which incorporated a series of 4 ventilation fans as shown in Figure 5. The module had an air gap of approximately 5 cm between the back of the substrate and surface onto which it was attached. This allowed air to flow through the substrate and out of the ventilators, as shown in Figure 1, image 2.

Figure 5: Vertical garden and supporting module.

A Lascar EL-USB-2-LCD digital thermometer was used to take all dry bulb temperature and relative humidity measurements (Figure 6). The digital thermometer was set to take measurements every 10 seconds.

Figure 6: Themohigrometro LASCAR EL-USB-2-LCD

The vertical garden module was saturated with water immediately before the experiment was begun. Excess water was allowed to drain away before turning on the fan and taking temperature and humidity measurements.

A control measurement was first taken of the ambient temperature and humidity levels. Following this, the measurement procedure for the vertical garden as a swamp cooler was:

- The ambient temperature and relative humidity was measured for approximately 1 minute.
- The temperature and relative humidity of the air coming out of one of the vertical garden ventilation fans was measured for approximately 1 minute.
- The ambient temperature and relative humidity was measured once again for approximately 1 minute.
- The process was repeated for each ventilation fan of the vertical garden.

Furthermore, it was necessary for this research to determine the wet bulb temperature, using the dry bulb temperature and relative humidity levels measured. This conversion was made using tools provided by the National Weather Service (NWS) [16].

3. Results

Figure 7 shows the results of the control measurements taken.

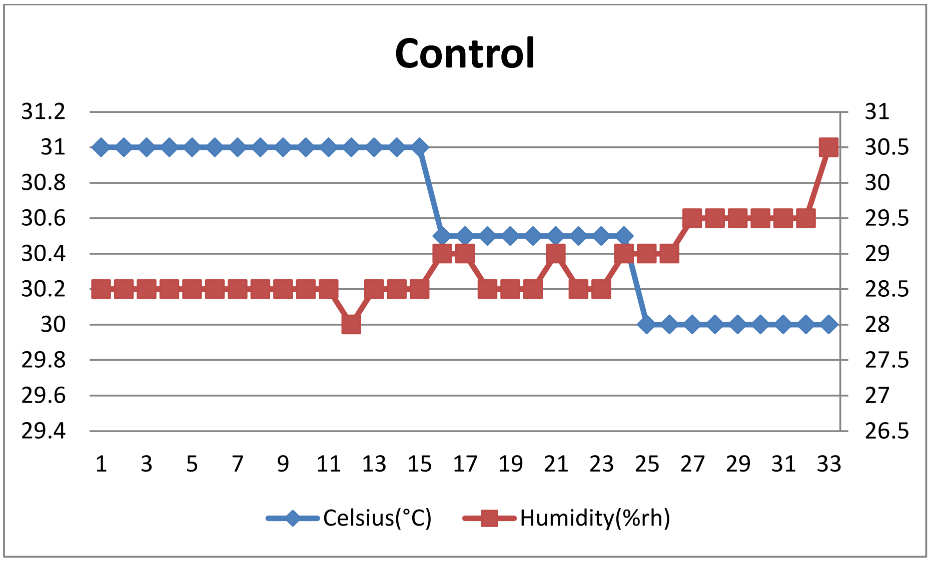

Figure 7: Control measurements taken of the ambient air temperature and relative humidity levels.

It is clearly shown that within the short period of time that the measurements were taken, there was a significant variation in temperature and relative humidity levels.

For the experimental results, it was therefore necessary for numerous measurements to be made, until results were obtained where the cooling of the air was due to it being drawn through the garden substrate, and not to variations in the ambient climate. The difference between a typical measurement where changes to the ambient climate are suspected, and a measurement where the ambient climate seems to remain stable, are shown in Figure 8 and Figure 9 respectively. Further research would be recommended, where simultaneous temperature and relative humidity measurements are made of the ambient climate and of the air coming out of the vertical garden.

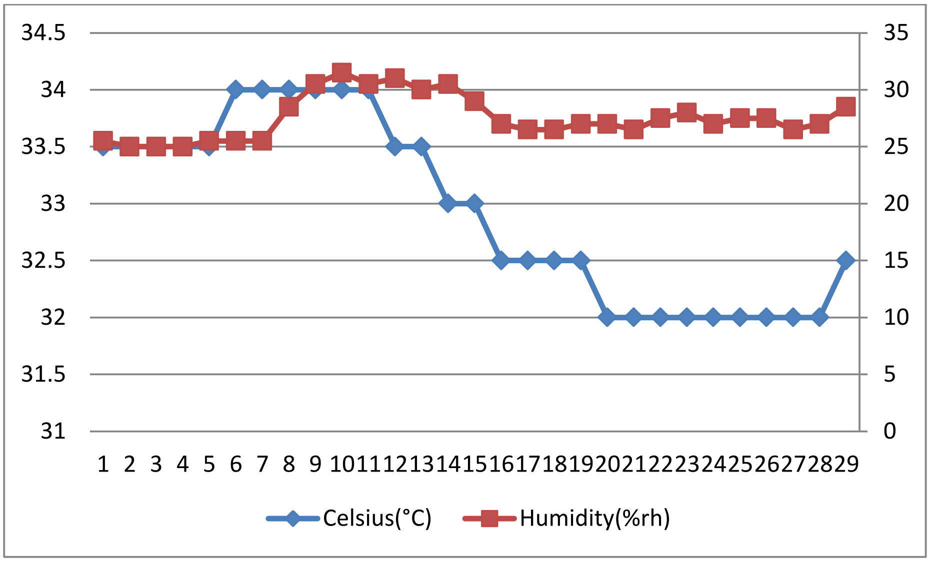

Figure 8: Measurements where changes to the ambient climate dominate.

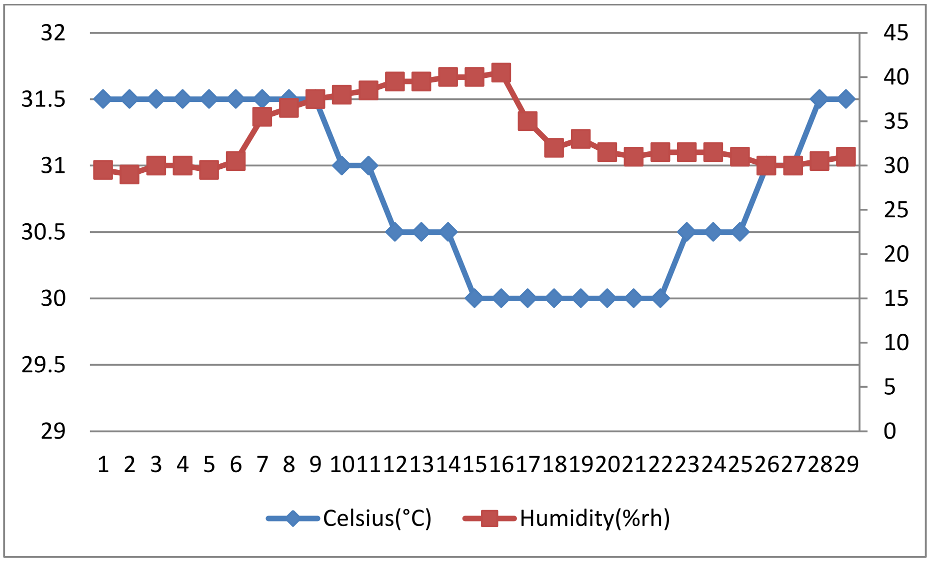

Figure 9: Measurements where the changes due to the garden substrate dominate.

Figure 9 shows the values adopted to quantify the effectiveness of the vertical garden as a swamp cooler. The ambient temperature and humidity levels were taken as the average from the ambient measurements before and after measuring the outgoing air from the ventilator fan. The temperature and relative humidity of the air coming out from the ventilator was taken as the maximum humidification of the air flow (Figure 10).

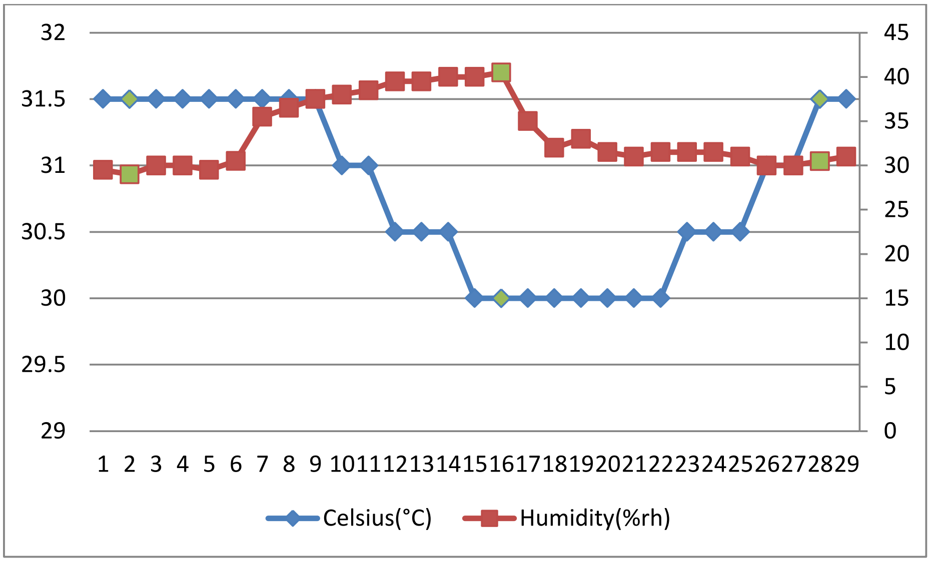

Figure 10: Values taken for temperature and relative humidity levels.

This gives the following values to determine the efficiency of the garden as a swamp cooler:

T_{db} = 31.5 °C
RH_{db} = 29.75%
T_{cooled} = 30 °C

Where:
T_{db} = Temperature of the incoming air before passing through the vertical garden substrate [°C]
RH_{db} = Relative humidity of the incoming air before passing through the vertical garden substrate [%]
T_{cooled} = Temperature of the outgoing air after passing through the vertical garden substrate [°C]

From this the wet bulb temperature could be determined using tools provided by the NWS [16]:
T_{wb} = 17.2 °C

4. Discussion of Results

Putting the results into Equation (2), it can be determined that:

$$\varepsilon = \frac{(T_{db} - T_{cooled})}{(T_{db} - T_{wb})} = \frac{(31.5-30)}{(31.5-17.2)} = \frac{1.5}{14.3} = 11\%$$

This is well below the efficiencies of commercial swamp coolers, which according to ASHRAE [1] are up to 90% effective in hot and dry climatic conditions. It does nevertheless represent a significant decrease in cooling demands, and could be connected in series to an air conditioning unit as a preliminary cooling mechanism to reduce the overall energy demand.

Furthermore, it shows that out of the three possible methods for cooling with vertical gardens, the most promising to date seems to be Method 2 of Davis & Ramirez [2], where the air flows behind the vertical garden, in the space between the substrate and the surface onto which the garden was attached. In this mechanism the air is cooled and humidified through its contact with the humid substrate.

4.1. Airflow behind the substrate and the vertical garden as an evaporative cooler

The next stage of this paper explores the experimental results for Method 2 of Davis & Ramirez [2] in greater detail. Their vertical garden module was similar to the one used for this paper, but where an airflow could be induced behind the substrate, in the space between the substrate and the supporting module (Figure 1, image 2).

In this case the further the air flows behind the vertical garden, the more it is cooled and humidified through its contact with the humid substrate. Therefore, the taller the garden the more the air is cooled, until the air is saturated to a point where it cannot be humidified any further.

Davis & Ramirez [2] found there to be a close correlation between their experimental results and those predicted by a mathematical model. For this study Davis & Ramirez's mathematical model has been adopted, but where the ambient temperature and relative humidity measurements taken from this research were used as input data. The mathematical model can then be run to determine what distance behind the substrate the air would need to flow, in order for it to be cooled and humidified to a comfortable temperature and relative humidity.

In terms of comfort, the Predicted Mean Vote of Fanger [17], ASHRAE's Graphic Confort Zone Method in the Standard 55-2010 [18], and the adaptive comfort guidelines of the ISSO 74 (2004) are used for this paper.

The climatic data measured in the experimentation for this paper was:

- Ambient dry bulb temperature of 31.5 °C.
- Relative humidity of 29.75 %.

When these are put into the mathematical model of Davis & Ramirez [2], a vertical garden of 3 m height would give the following values for the air that flows behind the substrate:

- Dry bulb temperature of 25.5°C.
- Relative humidity of 50.3 %.

This is shown in Figure 11 and Figure 12 respectively

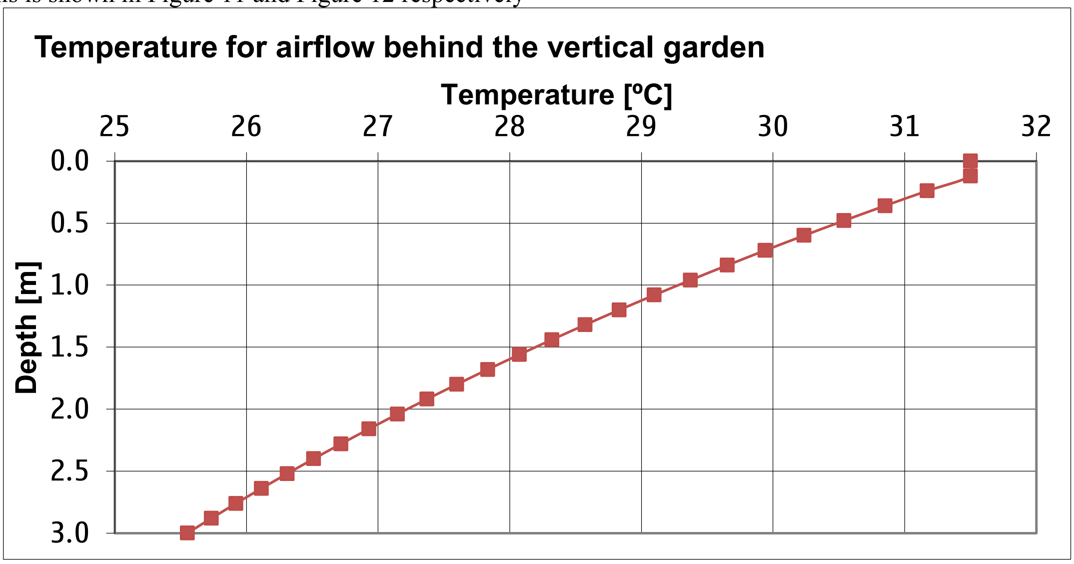

Figure 11: Temperature for airflow behind the vertical garden.

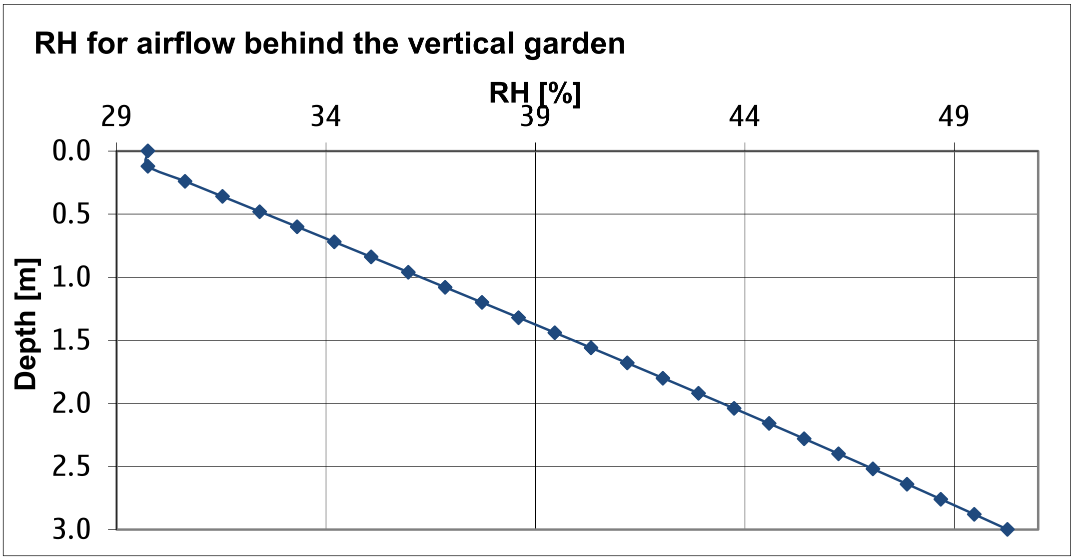

Figure 12: Relative humidity for airflow behind the vertical garden.

If the building's occupants wore light summer clothing (such as trousers and a long-sleeved shirt), and assuming that no additional radiant temperature loads are exerted, then this would give a PMV of approximately 0.2 [19] using Fanger's comfort model, and would be well within the comfort zone according to ASHRAE 55-2010 [18]. Furthermore, if it is assumed that the ambient measurements are similar to the Running Mean Temperature, then this would give a Class A of the ISSO 74 Adaptive Guidelines. The air temperature and humidity levels of the air flowing out from behind the substrate of a 3 m high vertical garden, could therefore be considered to be comfortable.

Finally, it is an interesting theoretical exercise to quantify the volume of indoor space that could be climatised using such a 3 m high garden. In order to do this a simplified office space is considered. Being a purely theoretical exercise it is assumed for now that no internal heat loads exist in the room. It is also assumed that at least 5 air exchanges per hour occur, in order to have sufficient fresh air [20]. Additionally, it is assumed that the air ventilated into the room is equal to the air leaving the room (conservation of mass). Lastly, the temperature and relative humidity of the incoming air is assumed to be equal to that of the experimental results, and the cooled air from that of the theoretical 3 m high garden:

- Incoming air: 31.5 °C, 29.75 %.
- Outgoing air: 25.5°C, 50.3 %.

Davis & Ramirez [2] measured the air velocity at the inlet, as the air began to flow behind the substrate. They also measured the space between the substrate and the supporting module. Additionally their garden module was 0.9 m wide. The values were:

V	= air velocity at the inlet	= 3.5 [m/s]
b	= breadth gap	= 0.05 [m]
w	= width garden	= 0.9 [m]

From these values the mass flow rate of cooled air from the garden can be calculated as:

$$V \times b \times w = 3.5 \times 0.05 \times 0.9 = 0.189 \text{ [m3/s]} \quad (4)$$

Then we can convert this to an hourly mass flow rate:

$$0.189 \times 3600 = 680.4 \text{ [m3/hr]} \tag{5}$$

This value can then be divided by 5, to give the typical air exchange rate required for offices:

$$680.4/5 = 136.1 \text{ [m3/hr]} \tag{6}$$

This can then be represented visually, by incorporating the vertical garden into a room 3 m high, 5 m wide and 9 m long (135 m3), shown in Figure 13.

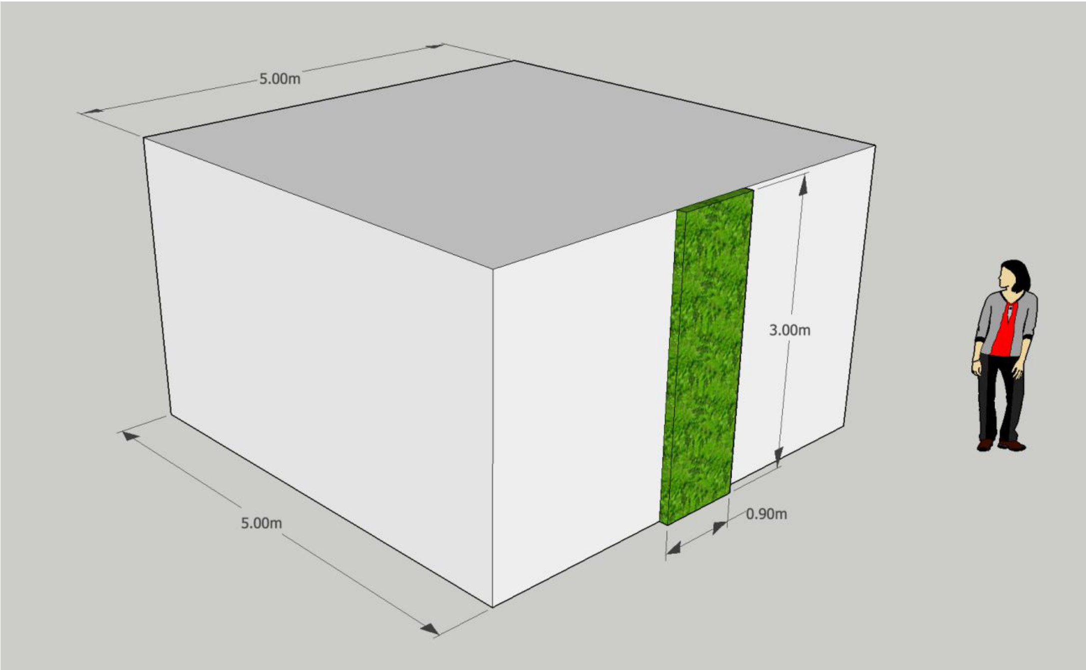

Figure 13: A visual representation of the space climatised by a vertical garden.

It can be seen here that even though the internal heat loads have not been included in this theoretical exercise, there is plenty of room for expansion for the vertical greenery to be incorporated into the architectural design. Needless to say, it can also be argued that the vertical garden is far more pleasing to the eye than standard air conditioning units often affixed to building exteriors.

Overall, this opens up the possibility for vertical greenery to be incorporated into building design, not only as an aesthetic addition to the façade and as a passive cooling system, but also as an integral part of the building's climatisation system. Further research is needed to quantify full scale, building incorporated vertical gardens for this to be explored in greater detail.

5. Conclusions

This research shows that the vertical garden had an efficiency much lower than that of commercial swamp coolers (11% vs. up to 90%). Nevertheless, this could represent a significant reduction in the energy demands for cooling, if the garden were connected in series to a building´s air conditioning system.

The experimental results show that to date the most promising manner for active vertical gardens to be used as cooling systems, seems to be Method 2 of Davis & Ramirez [2]. In this case the air is drawn into the space between the back of the substrate and the surface onto which the vertical garden is attached. Using the ambient temperature and relative humidity measurements from this research, it was shown that a 3 m high, 0.9 m wide vertical garden could potentially climatise an empty office space 3 m high, 5 m wide and 9 m long. Additionally, there would be plenty of room for expansion of the vertical gardens incorporated into the architectural design, in order to meet further internal cooling loads if required.

Overall, it has been shown that there exist various possibilities for vertical gardens to be activated as an integral part of a building's air conditioning system, and as such become more than solely a green façade.

6. Recommendations for further research

It is recommended that for future research simultaneous measurements are made of the temperature and relative humidity levels, both for the ambient environment and the airflow coming out of the vertical garden. This would solve uncertainties due to changes in the ambient climate whilst measurements from the vertical garden are taken.

Additionally, this paper has shown that air flowing behind a 3 m high vertical garden has a great potential to climatise a 136 m3 office space. It would therefore be recommended to construct such a garden in order for this to be explored further.

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