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POTENTIAL OF THE SEAWATER GREENHOUSE IN MIDDLE EASTERN CLIMATES

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SUMMARY

The Seawater Greenhouse is a method of cultivation that provides desalination, cooling and humidification in an integrated system. Its purpose is to provide a sustainable means of agriculture in arid coastal areas where the scarcity of freshwater and expense of desalination threaten the viability of agriculture.

Because the desalination process is driven mainly by solar energy, sunlight is the weather variable that most influences the performance of the Seawater Greenhouse. Correspondingly, the potential in Middle Eastern climates is excellent. However, other variables such as wind and humidity are also significant and this means that the optimum design and mode of operation may vary across the region.

In this paper we describe the Seawater Greenhouse system. We make reference to installations in the Canary Islands and the United Arab Emirates and to the installation now in progress in Oman. The experiments with these developmental versions have led us to create some mathematical models, enabling us to simulate performance in different climates. We analyse historical weather data for some Middle Eastern locations, including the Gulf of Aqaba, and discuss the effects these are likely to have on design considerations and performance.

1. INTRODUCTION

It is hardly necessary to state the dangers posed by the scarcity of fresh water. In recent years, the seriousness and extent of the problem has prompted a number of detailed studies into its causes and consequences such as that of reference1.

Nowhere is the problem more acute than in the Middle East. Most states in the region can be catagorised as suffering from severe water stress, with water consumption greatly exceeding the available renewable resource. Agriculture accounts for a very large fraction of water usage, averaging 87% for the MENA region as a whole[2,3]. As a result, water shortage has far-reaching consequences in terms of food supplies[4] and dependence on imported food.

Meanwhile, there is a growing opinion that future solutions should involve not only cheaper and better ways of providing freshwater, but also more economical ways of using this increasingly precious resource.

In a certain sense, agriculture is very inefficient in its use water. Of all the water used to irrigate crop, less than 1% can be expected to find its way into the final edible produce. Even in efficient irrigation systems, a very large fraction of the water is lost through transpiration.

Plant scientists have studied mechanisms of water loss in great detail. The classic model for representing water loss from crops is the Penman equation which compares the process to evaporation from an open pool of water[5]. In simple terms the equation can be written as:

$$\text{Rate of water loss} = b\,R + c\,D \qquad [1]$$

Where R is the net radiation received by the crop. The term D is the vapour deficit, meaning the difference between the saturation vapour content of the air and its actual vapour content. The terms b and c are approximately constant for a given range of conditions.

The Penman equation suggests two strategies for reducing water requirements.

(i) Reduction of the radiation R by means of shading; or possibly selective shading to favour photosynthetically active wavelengths of light.

(ii) Reduction of the vapour deficit D through humidification of the air.

Both of these strategies have been employed in the Seawater Greenhouse. In addition, the Greenhouse addresses the issue of excessive water loss from crops by incorporating them in a system that recovers some of the water transpired. The Seawater Greenhouse combines, in a single system, desalination with a water-efficient method of cultivation.

2. THE SEAWATER GREENHOUSE IN TENERIFE

The first prototype of the Seawater Greenhouse was constructed near Granadilla, in the south of Tenerife, in 1994. The project was funded by the European Community and involved a number of European research centres[6]. This was partly the reason for choosing Tenerife as a site, since the island is in Spanish territory. The prototype was used to cultivate a variety of crops including tomato, spinach, dwarf pea, pepper, artichokes, French beans and lettuces. Some of these, such as lettuces, are quite salt-intolerant but were nevertheless cultivated very successfully despite being within about 60 m of the sea.

The main structure of the greenhouse covered an area of 360 m^2 which became completely planted with crops. Some areas around the Greenhouse were also irrigated allowing indigenous vegetation to be re-established on this very arid and windswept coast.

Figure 1: The Seawater Greenhouse in Tenerife, 1994.

The Greenhouse faced into the prevailing wind that it collected through its front wall, this being a porous structure continuously wetted with seawater. The result of the air coming into contact with this large moist surface was a substantial humidifying and cooling effect. Figure 2 compares internal and external temperatures over a period of a week in the summer of 1995. Corresponding internal and external humidities are shown in Figure 3.

The pressure of the wind was sufficient to drive the air through two further elements: a second wetted wall at the back of the greenhouse and finally through a tube-and-fin type condenser. This condenser was fed with cold seawater causing freshwater to condense on its surface. Water production was typically at the rate of 1.5 m^3/day.

The water was of excellent quality, generally containing less than 50 ppm total dissolved solids (TDS). It was used to irrigate the plants via a drip irrigation system and water usage ranged from 0.6 to 1.2 l/m^2/day. This is several times lower than traditional outdoor cultivation which typically consumes 7 to 8 l/m^2/day.

At a number of locations around the world, cold sea water is available where coastlines plunge deeply into the sea or where cold upwellings occur. Tenerife is an example, and the condenser of the Greenhouse was suitable for receiving cold water from an offshore pipe. The design could accommodate up to six such condensers. The economies of scale of offshore pipes mean that they become viable for large projects. This is because the flow of seawater that can be collected through a pipe, for a given differential head, rises sharply as the diameter of the pipe is increased. Thus a pipe of, say 14” diameter can carry about 4 times as much water as one of 10” diameter, whereas the difference in diameter does not make a huge difference to the cost, which is more associated with the laying of the pipe rather than the material itself. For pipes of diameter below about 10”, warming of the water before it reaches the shore can become an issue.

A finding of the project was that the offshore pipe idea would become viable for projects covering more than 1 hectare (10 000 m^2) in Tenerife and similar locations. This was beyond the scope of the project, therefore for the purpose of the prototype the cold water was supplied from a commercial heat pump instead.

Water is an effective absorber of the infrared part of the solar spectrum, which is not photosynthetically active. The roof of the Tenerife Greenhouse was made of a double layer of fibreglass sheet thus providing a cavity into which seawater was sprayed. The system, although effective as optical filter, was troublesome in terms of leaks and had to be abandoned.

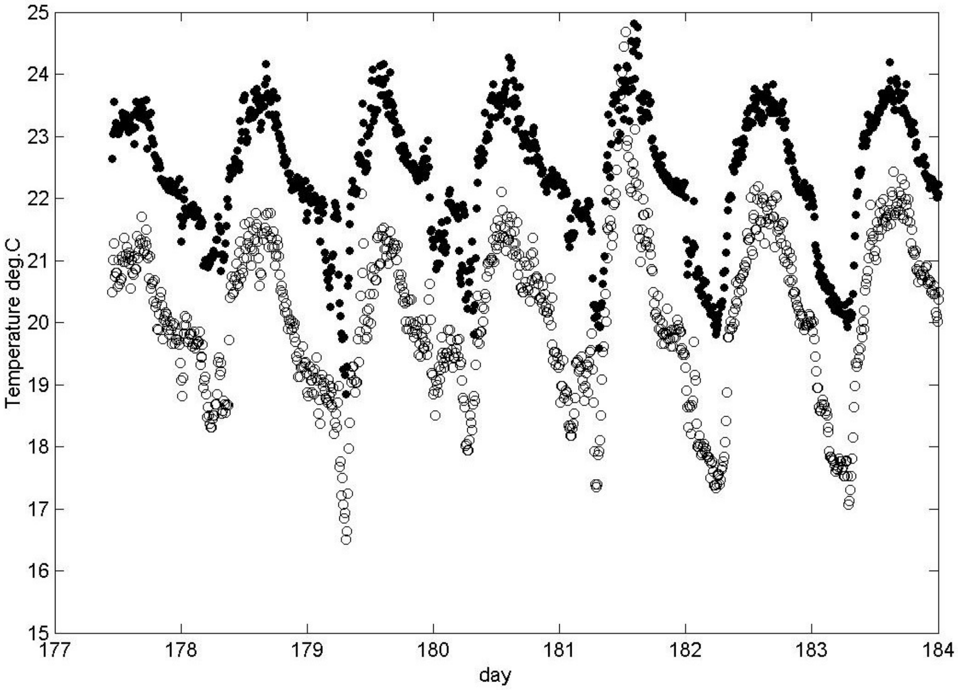


Figure 2: External (●) and internal (○) temperatures measured for the Seawater Greenhouse in Tenerife, 1995. The day numbers are counted from the beginning of the year.

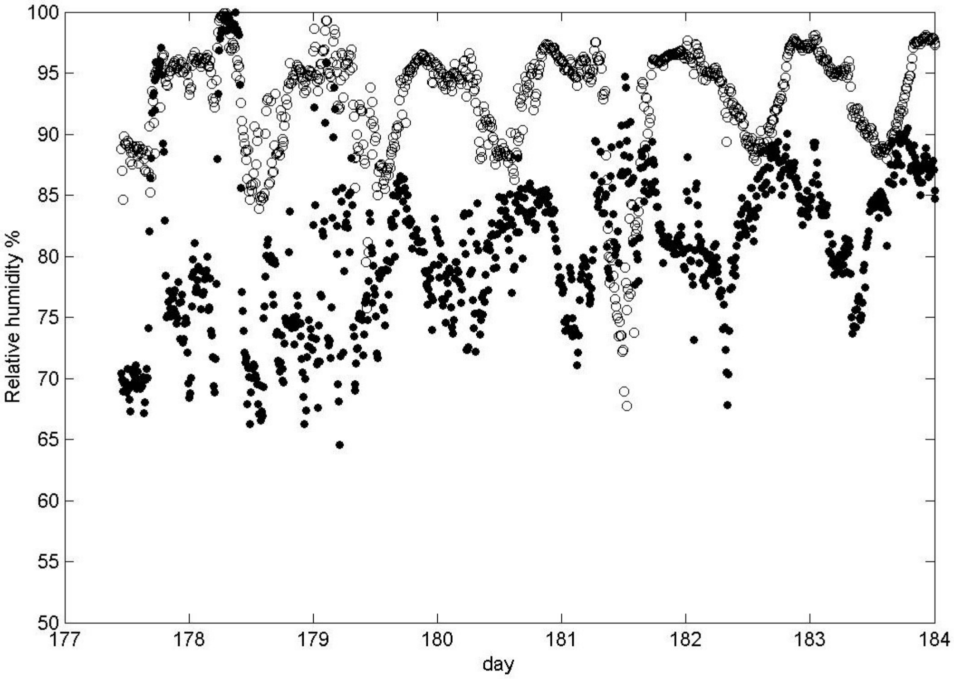


Figure 3: External (●) and internal (○) humidities measured for the Seawater Greenhouse in Tenerife, 1995.

2. THE SEAWATER GREENHOUSE IN THE UAE AND OMAN

Following the Tenerife experiments, the drive became towards a low-cost design that did not depend on any special oceanographic conditions. It was desirable to be able to demonstrate the design on a small scale if necessary, as the concept was still somewhat experimental and large projects might therefore be difficult to fund. These considerations led us towards the concept of using cold water collected from the front wall of the Greenhouse to feed into the condenser at the back, in place of cold water piped from the sea.

The concept was demonstrated in the Seawater Greenhouse constructed in December 2000 at Alaryam in the United Arab Emirates (UAE), as a result of a collaboration with the Emirates Centre for Strategic Studies and Research (ECSSR). This Greenhouse, covering 864 m^2, is still in operation producing crops year round.

At the start of operation, water yield from the Greenhouse was somewhat lower than expected. However, a number of improvements were implemented such that water production approached 1 m^3 per day, sufficient to meet the irrigation demand of the crops. The main change was to add an array of tubes providing solar heating to the seawater being fed into the second evaporator wall of the Greenhouse.

As in the Tenerife Greenhouse, the product water was of excellent quality with TDS of 9.75 ppm.

Figure 4: Tomato crop growing inside the Seawater Greenhouse in the United Arab Emirates, June 2001.

A selective light filter made of commercial polyethelene film was used to shade the crops, in place of the wetted roof design in Tenerife. However, whereas this film was a fraction of the cost of a conventional thermal screen, it was found to be less than ideal in terms of temperature control.

As a result of the work in the UAE, we are now planning a further Greenhouse, to be constructed as part of a joint project with the Sultan Qaboos University in Oman. The essential design concept of the Greenhouse is shown in the diagram of Figure 5.

The basic configuration is similar to the UAE. There are two main seawater circuits, one comprising the first evaporator (at the front wall) and the condenser, the other comprising the second evaporator (at the back wall) and the tube array used for solar heating. This tube array is now to be integrated into the greenhouse roof, thereby combining the functions of providing shade and boosting freshwater production.

A second development in this Greenhouse is the introduction of the all-plastic *Watermaker* condenser which is of lower cost and yields more water per kJ of heat transferred, compared to the previous tube-and-fin condenser made of cupronickel and aluminium.

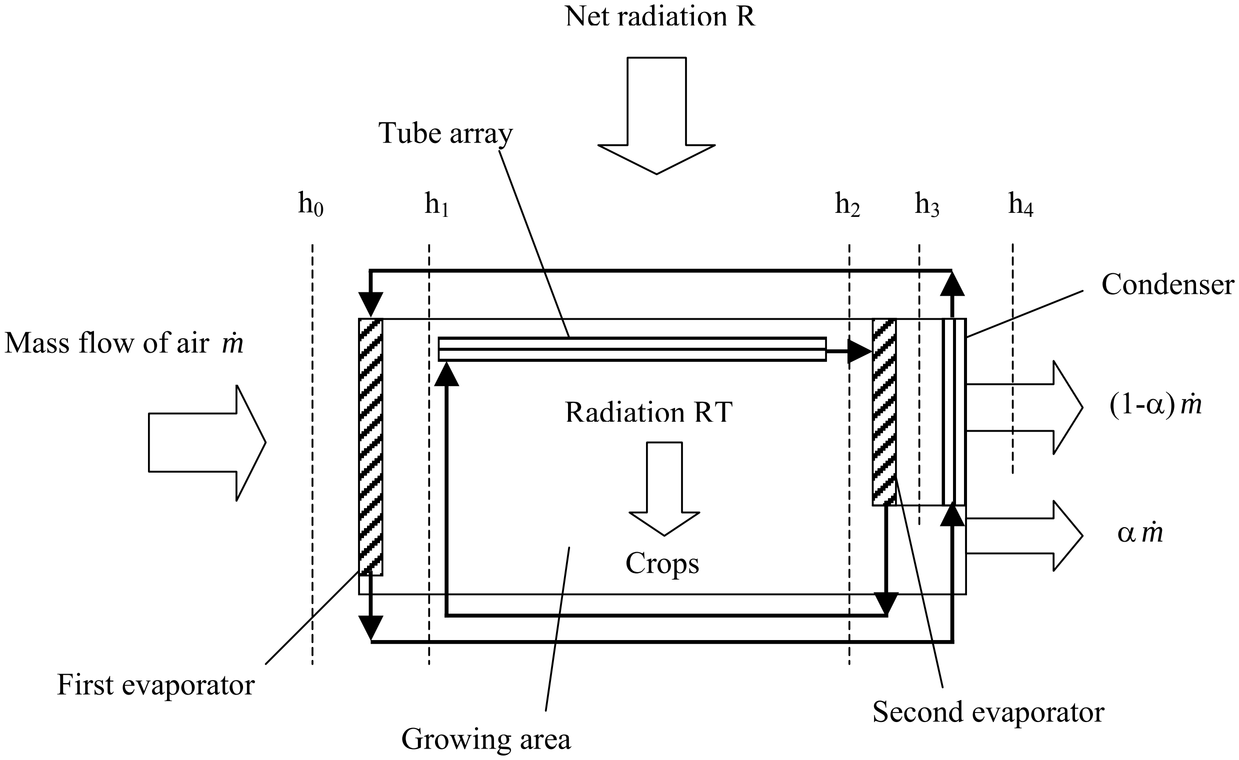


Figure 5: Schematic of Greenhouse as developed for Oman. The heavy arrows indicate flow of seawater.

3. MATHEMATICAL MODELLING

A number of theoretical models have been developed and validated alongside the design and operation of these Greenhouses. The models have become invaluable for predicting the effects of varying design parameters and are used as a design tool.

The models are useful for drawing some conclusions about the system both generally and in the case of the Middle East.

3.1 Wind modelling

The Seawater Greenhouse interacts with the wind and the Tenerife prototype demonstrated that ventilation and cooling could be achieved by wind alone, without using any fans to move the air.

The Tenerife climate is windier than Middle Eastern climates. In addition, the very high temperatures in the Middle East make overheating more of a risk in the case of low windspeeds. For these reasons we use fan ventilation in Middle Eastern applications.

On the other hand, the new *Watermaker* condenser has a lower air resistance than the previous design and this introduces the possibility of using wind-driven ventilation at least some of the time at sites where conditions are suitable. The advantage would be power saving in the operation of the fans. For reference, the current design uses two fans each having a nominal rating of 0.75 kW. These are used with a speed controller such that actual power consumption varies from 0.25 to 1.4 kW in total.

To assess the availability of wind at any particular site, we need to understand the effect of wind direction on ventilation. The aerodynamics of the greenhouse have been studied with the help of wind tunnels, computational fluid-dynamic (CFD) analysis and measurements on the real greenhouse.

Figure 6 shows the flow field around the Tenerife Greenhouse as obtained from 3-dimensional CFD analysis. The model was used to vary the angle of attack θ of the wind. The results, in terms of the wind-angle acceptance function $f(\theta)$, are shown in Figure 7. The wind-angle acceptance function is defined as the ratio of the air flow, for a given angle θ, divided by the airflow resulting from wind approaching the Greenhouse perpendicularly ($\theta = 0$).

$$\textit{Airflow} = \textit{constant} \times \textit{ambient wind velocity} \times f(\theta) \qquad [2]$$

It turns from the CFD that $f(\theta)$ can be approximated well by a cosine function, as illustrated by the polar graph of Figure 7. Verification of this against measurements from the Tenerife Greenhouse is shown in Figure 8.

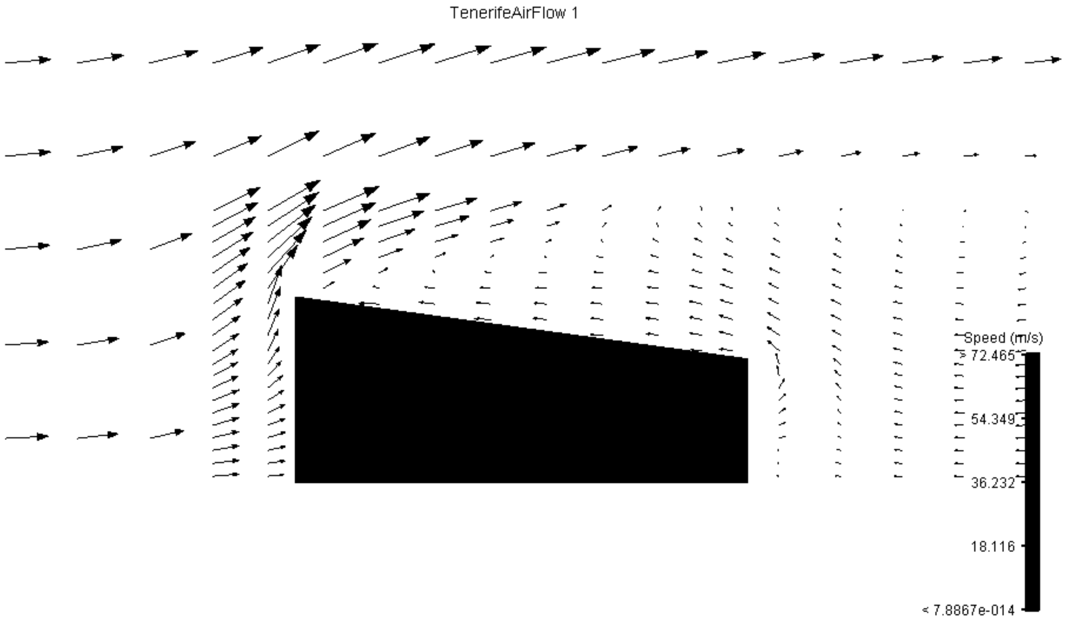


Figure 6: Visualisation of the flow field around the Tenerife Seawater Greenhouse, obtained using the CFD program *Flovent*.

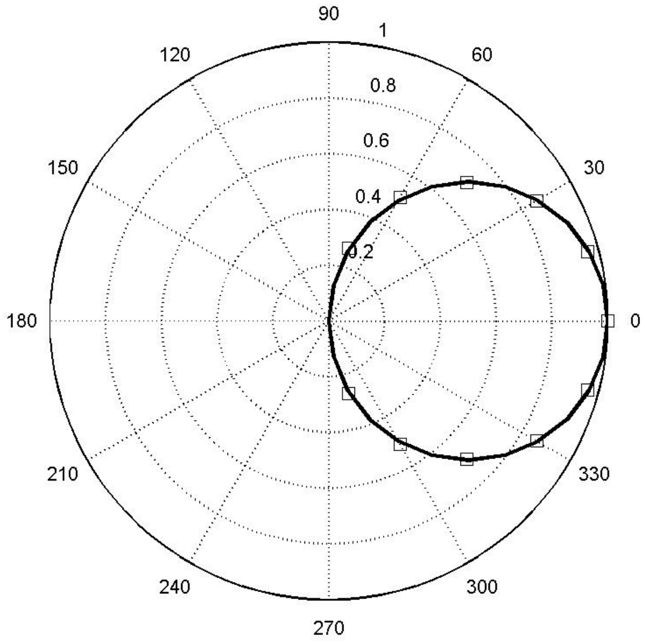


Figure 7: Polar plot of the wind-angle acceptance function f(θ): □ from CFD modelling, — cosine model *f*(θ)=cos(θ).

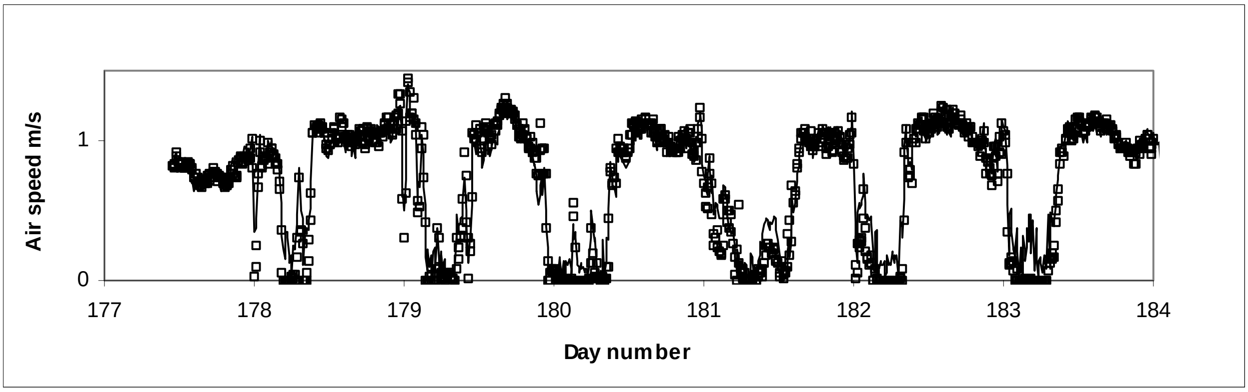


Figure 8: Verification of the cosine model (–) against measurements of airspeed at the condenser of the Tenerife Greenhouse(□).

Based on the cosine model, we can compare the wind availability of different sites in the Middle East based on time series of wind speed and direction data taken from meteorological stations[7]. At each moment in time, we calculate the component of wind in the prevailing direction for the given site. Only daytime values are used, as the Greenhouse requires only minimal ventilation at night. This yields a time series of effective wind speed.

To summarise these values we then determine the median value (see Table 1). Thus, a median value of 4 m/s would suggest that, if we designed the Greenhouse such that a 4 m/s wind were sufficient to provide wind-driven ventilation, then fans would only be needed for the remaining half of the time. A 50% power saving would then be achieved.

Table 1: Median effective wind speeds at various Middle Eastern locations. Tenerife is included for reference. The prevailing direction, measured in degrees from North, is the angle in which the Greenhouse should be pointed for maximum ventilation. Where a range is shown, this indicates that the median effective wind speed is insensitive to the direction within this range.

Location	Prevailing direction deg. from N	Median effective speed m/s
Tenerife	90	6.3
Sharm-el-Sheikh	20	4.8
Aqaba	15	4.0
Jeddah	290 – 320	4.6
Salalah	190	3.6
Qarn Alam	180	2
Muscat	40	3.0
Abu Dhabi	330	4.4
Kuwait	310 – 360	3.1

From Table 2 it can be seen that, whereas all Middle Eastern locations have less wind than Tenerife, the potential for wind ventilation at certain locations such as Aqaba, Sharm-el-Sheikh, Abu Dhabi and Jeddah is significant. Of course, these data are taken from meteorological stations, mainly at airports. Local wind conditions vary due to the influence of topographical features.

The Seawater Greenhouse requires a supply of seawater and discharges seawater into the sea. It is therefore intended for use near the coast. On the other hand, oil wells often dispose of large quantities of production water, which can be seawater piped in from the coast. This introduces the possibility of building Greenhouses inland. The Greenhouse could make use of the production water either before or after it has been used in the oil well. As an example of inland operation, we have analysed wind data available for Qarn Alam (Oman). It can be seen from Table 2 that the potential for wind ventilation is rather low in this case. This is because, unlike at the other locations, which are coastal, the wind lacks directionality. Ventilation by fans alone would probably be preferred in this case.

3.2 Simplified thermodynamic modelling

The large number of processes occurring simultaneously in the Seawater Greenhouse means that simple analytical models are not usually accurate and that computer models have to be used. On the other hand, simple models are useful in exposing the relations among the main parameters. They can also give some indications of performance under a set of idealised assumptions, enabling the real performance to be compared against the ideal. Areas for improvement can then be identified.

The basic method of analysis is heat and mass balance. Under approximately steady-state conditions, it is possible to write a heat balance equation for each stage of the process shown in Figure 5. The symbols in the following equations are defined in Table 2.

Regarding the two seawater circuits shown in Figure 5, some bleed off and top up is needed otherwise the concentration of the seawater would keep on increasing. However, these flows are much smaller than the circulating flows and are therefore ignored in the heat balance calculations. The first evaporator is in the same circuit as the condenser, so the heat added at this stage equals that removed by the condenser:

$$\dot{m}(h_1 - h_0) = \dot{Q} \qquad [3]$$

Between the inlet and outlet of the growing area of the Greenhouse, the heat added corresponds to the net radiation received over the plan area, multiplied by the fraction of light transmitted through the tube array:

$$\dot{m}(h_2 - h_1) = RAT \qquad [4]$$

The first evaporator must be capable of producing sufficient water at the wet-bulb temperature to feed the condenser. For this to be the case, there must more air flowing through the evaporator than through the condenser. This is achieved by allowing a fraction α (typically $0.5>\alpha>0.3$) of the air that leaving the growing area to bypass the condenser. Therefore, the mass flow rate is reduced to the fraction $(1-\alpha)$ at the second evaporator. The heat addition corresponds to the radiation captured by the tube array:

$$(1-\alpha)\dot{m}(h_3 - h_2) = RA(1-T) \qquad [5]$$

The rate of heat removal in the condenser is:

$$(1-\alpha)\dot{m}(h_3 - h_4) = \dot{Q} \qquad [6]$$

Let us introduce the expression for the effectiveness of the condenser, based on the enthalpy drop on the air side:

$$\varepsilon = \frac{h_3 - h_4}{h_3 - h_0} \qquad [7]$$

The maximum possible effectiveness of unity would correspond to the situation in which the air is cooled to the temperature of the water entering the condenser i.e. the ambient wet-bulb temperature. The enthalpy of the air, which is saturated at this point, would then be the same as the ambient enthalpy h_0. Note that it is more usual to define effectiveness in terms of the corresponding temperatures, but the definition in terms of enthalpy is convenient here and for small temperature ranges there is little difference between the two definitions.

Two simplifying assumptions are now introduced:

1. On leaving each of the evaporators, the air is saturated with water vapour. Although in practice 100% humidity is never reached, humidities above 95% can occur with a correctly designed evaporator. This is seen in Figure 4.

2. The amount of water contained in the saturated air is approximated by a linear function of enthalpy for the range of interest.

We wish to determine the conditions for the Greenhouse to be self-watering. The estimation of water use by plants using the Penman equation is complicated by the need to determine the constants in equation [1]. On the other hand, a simple approach is to say that the amount of water evaporated in the growing area cannot be greater than that required to result in the exit air (position 2) being saturated. This should give a conservative estimate of the amount of watering required.

Now, on the basis of assumption 2 above, the amounts of fresh water condensed in the condenser and evaporated in the planting area can be written purely in terms of mass flows multiplied by enthalpy changes. This leads to the following condition for the amount condensed to be greater than the amount evaporated, i.e. for self-sufficiency in water to be achieved:

$$\dot{m}(1-\alpha)(h_3 - h_4) \geq \dot{m}(h_2 - h_1) \qquad [8]$$

The enthalpy terms can be eliminated from the above system of equations. The inequality [8] then leads to the following result for the required effectiveness of the condenser:

$$\varepsilon \geq \frac{1}{1+(1/T)-2\alpha} \qquad [9]$$

The inequality shows that, as the fraction T of transmitted light is increased, a more effective condenser will be needed to produce enough water for the plants. This can be explained by the facts that (i) the greater radiation falling on the plants will lead to greater transpiration and (ii) the corresponding decrease in the amount of solar heat collected by the tube array will lower the rate of water production.

The inequality [9] is represented in Figure 9. It can be seen that, for a value of T of 0.5, the condenser effectiveness ε should be at least 0.45.

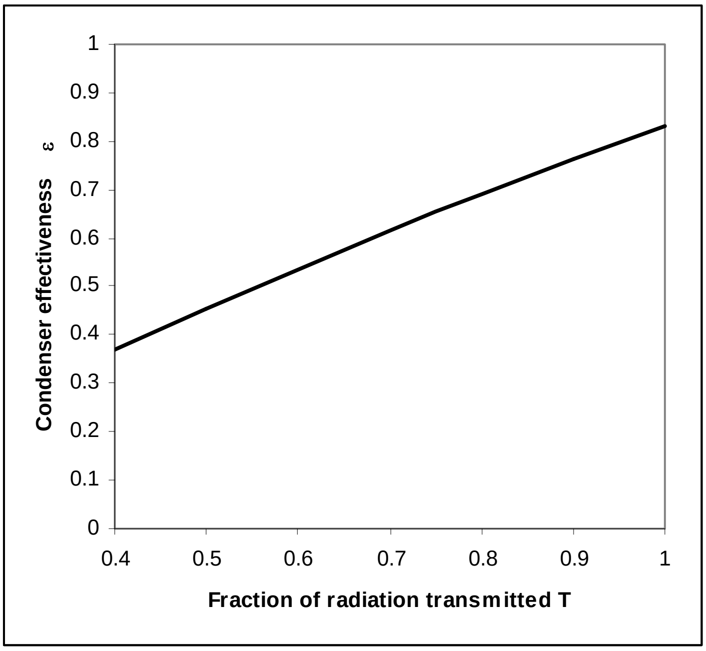


Figure 9: Required minimum effectiveness ε of the condenser to achieve self-watering for a given value of transmittance T of radiation of the tube array. Based on the simplified thermodynamic model, relation [9]. The value of α is fixed at 0.4.

Whereas increasing the size of the condenser would increase water production further, it is important to note that there could be a substantial cost penalty. For example, a condenser of ε=0.7 will tend to be about twice the physical size compared to one of ε=0.45.

Table 2: Symbols used in the simplified thermodynamic model, equations [3] to [9].

Symbol	Units	Meaning
A	m^2	plan area of Greenhouse
h_0	kJ/kg	specific enthalpy of ambient air
h_1	kJ/kg	specific enthalpy of air leaving first evaporator
h_2	kJ/kg	specific enthalpy of air leaving growing area
h_3	kJ/kg	specific enthalpy of air leaving second evaporator
h_4	kJ/kg	specific enthalpy of air leaving condenser
$\dot{m}$	kg/s	mass flow of air entering Greenhouse
$\dot{Q}$	kW	rate of heat removal by condenser
R	kW/m^2	net solar radiation flux
T		fraction of radiation transmitted to growing area
α		fraction of air bypassing the condenser
ε		effectiveness of the condenser

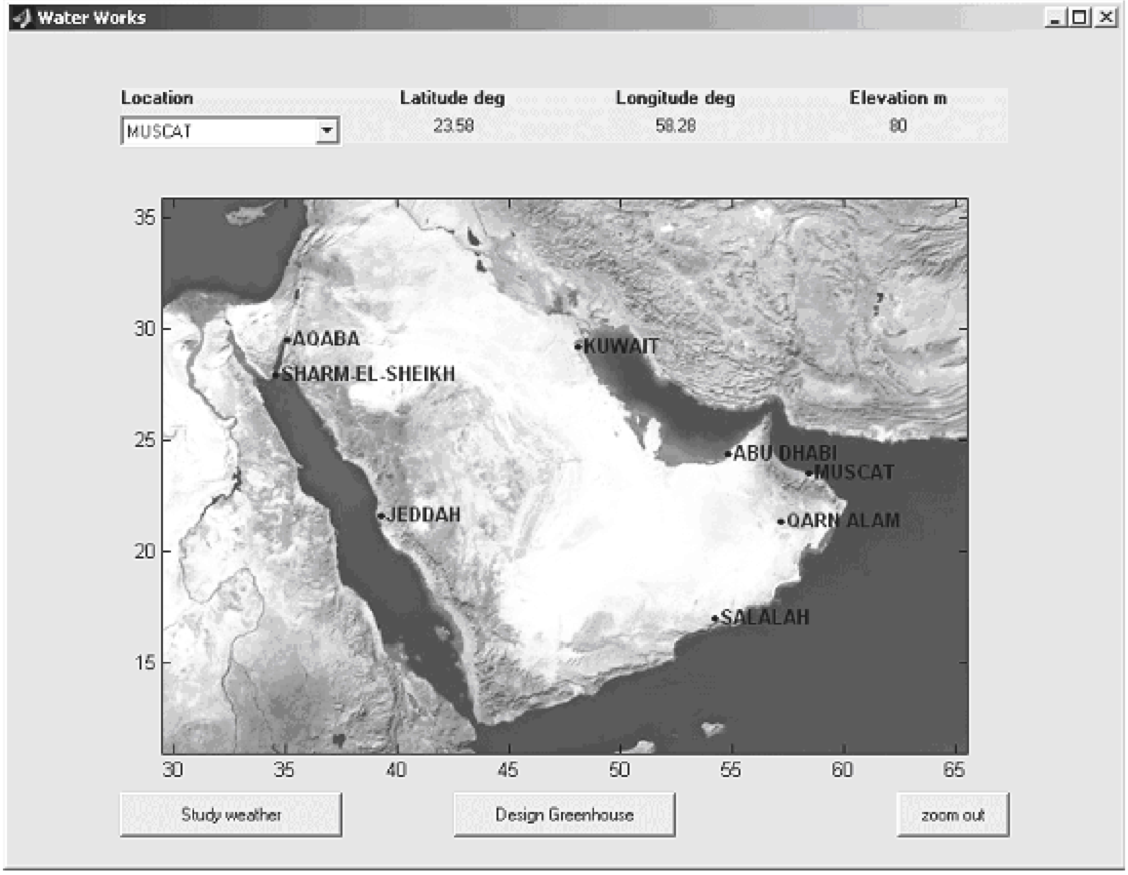
3.3 Detailed thermodynamic modelling

The simplified model provides the basis for the more detailed model that has been developed into a bespoke program called *Waterworks*, based on the MATLAB programming environment[8].

The detailed model includes a number of experimental corrections and correlations omitted from the simplified model. For example:

- Real performance of the evaporators, without assuming 100% saturation.
- Detailed model of the condenser, based on its size, with scaling from laboratory experiments with small-scale models.
- Heat loss or gain through the walls of the greenhouse.
- Simulation over a series of time steps, with varying inputs of ambient temperature, humidity, sunshine and wind.

The interface to the Waterworks program presents the user with a world map, allowing him or her to zoom into a region of interest and then select a potential Greenhouse site. Figure 10 shows the interface with the Middle East region selected.



Location	Latitude deg	Longitude deg	Elevation m
MUSCAT	23.58	58.28	80

Figure 10: Interface to Waterworks program.

The eight sites shown were selected to reflect a certain geographic spread and according to the data available, which was generated from references 7 and 9. Year-round simulations were performed to give values of annual water production for a Greenhouse of nominal area A=500 m^2, between the first and the second evaporator. The results are shown in Table 3 together with average ambient humidities. A variation in water production of about 25% is predicted among the sites. This correlates somewhat with the relative humidities. In Oman, a slightly larger water production can thus be expected at the inland site of Qarn Alam where conditions tend to be less humid than in Muscat (see comments in section 3.1 about the use of oil-well production water at inland sites). The relatively high water production at Kuwait and Sharm-el-Sheikh is due to drier offshore winds compared to the humid onshore winds at some of the other sites.

A lower relative humidity results in a lower wet-bulb temperature. This means that colder water is fed into the condenser. Meanwhile, the air is also entering the Greenhouse at a cooler temperature. This favours the absorption of heat through the walls of the Greenhouse. Further, it is possible to choose a slightly lower ventilation rate without encountering overheating in the greenhouse. Consequently, a larger temperature differential tends to occur at the condenser which favours heat transfer and fresh water output.

Table 3: Annual water productions from a nominal Seawater Greenhouse (A=500 m^2), based on simulations.

Location	Water production m^3/year	Average ambient relative humidity %
Sharm-el-Sheikh	325	41
Aqaba	275	59
Jeddah	265	63
Salalah	230	66
Qarn Alam	310	45
Muscat	260	59
Abu Dhabi	270	58
Kuwait	330	40

4. CONCLUSIONS

The principle of operation of the Seawater Greenhouse can be understood from the standard theory of crop transpiration based on the Penman equation. Effectively, the Greenhouse creates an environment in which watering requirements are substantially reduced compared to cultivation in the ambient environment. As a consequence, the value of the freshwater produced by the Greenhouse is enhanced, such that one cubic metre of product water substitutes for several cubic metres of water as used in more conventional cultivation.

The Seawater Greenhouse has evolved through the constructions in Tenerife and the United Arab Emirates. Aspects of these designs are being incorporated into a new project underway in Oman. The practical developments have been paralleled by mathematical models, which give projections of performance under various design options and site conditions.

The Middle East is an area of prime interest, due to the suitable climate conditions and the need for innovative solutions to the problems of water and agriculture.

The Greenhouse in Tenerife was ventilated and cooled by the wind without the use of any fans. Although fans are likely to be used in Middle Eastern projects, providing ventilation for at least some of the time, this study shows that certain sites in the Middle East have significant wind potential. The median effective wind speed at Sharm-el-Sheikh, for example, is 4.8 m/s compared to 6.3 m/s at Tenerife

A simplified thermodynamic analysis emphasises the importance of shading in the Greenhouse and correct sizing of the condenser that has been an expensive element of the Greenhouse. A low-cost condenser is currently under development.

The more detailed thermodynamic analysis, carried out by computer simulation, shows that a variation of about 25% may be expected among the sites studied. Larger rates of freshwater production tend to occur at sites with lower relative humidities. The use of the Seawater Greenhouse at inlands sites, where humidities are low and seawater may be available in the form of oil-well production water, may be an interesting possibility in spite of the fact that the Greenhouse is intended primarily for use on arid coastlines.

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