Desalination and Water Treatment
www.deswater.com

1944-3994/1944-3986

3 (2009) 229–235

Small-scale reverse osmosis brackish water desalting system combined with greenhouse application for use in remote arid communities

A.K. Hossain*, Philip A. Davies

Sustainable Environment Research Group, School of Engineering and Applied Science, Aston University, Aston Triangle, Birmingham B4 7ET, UK
Tel. +44 121 204 3041; Fax: +44 121 204 3683; email: a.k.hossain@aston.ac.uk

Received 30 September 2008; Accepted 23 February 2009

ABSTRACT

Thermal distillation and reverse osmosis (RO) membrane filtration are the most widely used water desalination technologies in the world. Thermal systems are generally associated with high consumption of energy and only efficient for large scale plants. RO systems are expensive but are widely used due to their high total dissolved solids (TDS) reduction capacity and good recovery rate. Energy consumption in RO systems varies almost linearly with the amount of TDS. In remote arid and semi-arid regions where grid electricity is not available, small diesel generator/battery-operated (constant flow) or solar-powered (variable flow) RO systems for brackish water desalting are attractive options. Safe and economic disposal of salt concentrate from the RO system is a troublesome issue. Solar-powered RO combined with a greenhouse application presents a sustainable environmental system. Evaporative cooling pads are widely used for greenhouse cooling in many parts of the world. Fresh water is used in the cooling pad. In this study, the salt concentrate from the RO module (simulated) is used to cool the greenhouse by passing it through an evaporative pad. The concentrate will then be allowed to evaporate into a solid in a pond to allow easy and safe disposal. Results show that evaporative cooling can be achieved successfully using RO concentrate in place of fresh water. The performance of salt water and fresh water cooling is compared. A pilot experiment shows that the reduction of RO concentrate volume is possible. Degradation of pad material performance, use of different pad materials and assessment of the cooling efficiency degradation with time are future activities to be carried out.

Keywords: Brackish water; Reverse osmosis; Solar PV; Arid zone; Evaporative cooling; Greenhouse

1. Introduction

The demand for clean drinking water is increasing alarmingly with the increase of world population. Safe drinking water is very important for protecting human health. The acquifiers has been over exploited due to the increasing demand of drinking water in many areas of the planet which results salt contamination.

Desalination is widely used to meet the water demand in areas with scarce water resources. Selection of the technology depends on the sample properties of the water need to be cleaned and end use. The technologies can be divided mainly into two groups: thermal and membrane. The thermal process is mainly one of distillation and is

---

*Corresponding author.

Presented at EuroMed 2008, Desalination for Clean Water and Energy Cooperation among Mediterranean Countries of Europe and the MENA Region, 9–13 November 2008, King Hussein Bin Talal Convention Center, Dead Sea, Jordan.

one of the oldest processes of purifying water. The disadvantage of this process is that the organics with boiling points lower than 100°C cannot be removed efficiently and can actually become concentrated in the product water. Another disadvantage is that the distillation process requires large amounts of energy and water. There are three types of commercial distillation processes: multi-stage flash, multi-effect and mechanical vapor compression.

Membrane filtration is a process whereby particles smaller than about 10^{-2} mm are removed using synthetic polymeric membranes and high pressure. It is increasingly becoming popular and various types are: microfiltration, ultrafiltration, reverse osmosis and nanofiltration. The reverse osmosis (RO) process offers quite low energy requirements [1]. Renewable energy has been used in many desalination plants around the world due to: (1) its environmental friendly nature and (2) non-availability of grid electricity supply to power the plant. Techno-economics of solar PV and wind turbine energy powered RO plants has been reported in the literature [1–5]. Solar PV–RO plants consume around half of the corresponding energy needed for thermal processes [2]. Hrayshat [2] developed a computer code of a PV–RO brackish water desalination system to predict water production capacity at different selected sites and at different months of the year; the input data used were: solar radiation, sunshine hours, and salinity of the feed water (TDS, 3000–10,000 mg/l). A concentrated solution-driven turbine wheel was integrated in the model for energy recovery [2]. Ahmed and Schmid [4] modelled a small-scale PV–RO system for predicting both the water production and plant economics. Fresh water production cost of the solar PV–RO brackish water desalting plant has been reported as US \$3.73/m^3 (based on the production capacity of 1 m^3/d) [4]. On the other hand, in the case of a wind turbine RO-based brackish water desalting plant; the water production cost has been reported as US \$2.9/m^3 [1].

A small-scale solar PV-powered brackish water RO desalination plant is an ideal technology for the production of fresh water in many arid/semi-arid regions of the world. However, discharge of brine/salt from RO plant is an environmental problem which poses a threat to the ecosystem. We presented a design of a solar PV-based RO desalting system combined with a greenhouse application at the 2nd Oxford water and membrane event based on the following [6]: (1) concentrate from the desalination process should be managed sustainably; (2) preferably fresh water produced should be for drinking as well as irrigation; (3) integration of rainwater if available since this is an inherently renewable and free resource. The design proposes that RO concentrate be used to cool the greenhouse where a reduction of volume is possible. The much concentrated volume will then be allowed to evaporate in a pond, which can be disposed of sustainably.

A growing population, water scarcity, food security, and global warming factors add to the need for an efficient and economic cooling system in greenhouses in hot climates. Evaporative cooling is an economic and effective way of controlling temperature and humidity inside a greenhouse. It requires less power consumption compared to air conditioning systems due to the use of a small water pump and a blower. Also the maintenance cost of such a system is comparatively lower than conventional refrigeration and air conditioning systems. At present, a disadvantage of evaporative cooling is the use of fresh water. Seawater-cooled greenhouses combined with desalination systems have been demonstrated in the literature [7–9].

This study focuses on the use of brackish water RO concentrate for greenhouse cooling. As a first step, a commercially available cellulose pad (CELdek) was used. The objectives of this study are to: (1) study RO concentrate management options, greenhouse cooling techniques and types; (2) study evaporative cooling principles and types of pads; (3) design and construction of the pilot experimental rig to simulate greenhouse cooling in the laboratory; (4) measure and compare the evaporative cooling performance using RO concentrate (salt water) and fresh water (control); and (5) observe salt deposits inside the cooling pad over a period of time.

2. Methods

2.1. RO concentrate management

RO concentrate management is an important part of the brackish water desalting plant feasibility study. It has been reported that while water production costs have been decreasing, concentrate management costs have grown [10]. RO concentrate should be managed in a cost-effective way in an environmentally safe manner. Some RO concentrate management options are [10]: (1) traditional disposal options, (2) less conventional disposal options, (3) beneficial use options, (4) volume reduction treatment of concentrate, and (5) zero liquid discharge treatment of concentrate.

Traditional disposal options are: discharge to surface water, discharge to sewer, deep well injection, land application, and use of evaporation ponds. The common methods used are discharge to surface water. A deep well rejection system is cost intensive, whereas rejection in sewers is the least costly. Disposal of concentrate to surface waters, sewers, and to land applications may result in salt loading of the receiving water. Finally, at some point future discharge would not be possible. So disposal via these options is not sustainable.

Less conventional disposal options are not widely used, but one example is the use of BWRO concentrate as partial feed for SWRO plants. This also leads to cost savings due to the reduced feed pressure and therefore reduced energy consumption at the SWRO plant [10]. Some of the beneficial uses of concentrate are: oil well field injection, solar ponds, aquaculture, wetlands, transport of mineral resources, subsurface storage, feedstock for hypochlorite generation, cooling water, dust control and de-icing and scrubber water.

Volume reduction of RO concentrate is performed through a 2nd-stage RO system. To avoid the limitation due to sparingly soluble salts and silica, either treatment of the concentrate to remove these species or combination of treatment and high pH operation of the second stage are typically employed [10]. Zero liquid discharge is widely used in industry including power plants. Mechanical vapour recompression evaporators are the most frequently used commercial technology taking the feed solution up to a brine concentration of 180,000 to 280,000 mg/l depending on the water quality. Brine from brine concentrators is typically sent to evaporation ponds or is further processed to dry salts by a thermal crystalliser or, if the volume is small, by a spray dryer [10].

2.2. Greenhouse cooling

Greenhouses are cooled either through natural ventilation, fan and shutter cooling, or by evaporative cooling techniques. Natural ventilation is used for mild climate regions. Fan and shutter techniques are used to maintain the temperature inside the greenhouse within ±10°C. Evaporative cooling is a process that uses the effect of evaporation as a natural heat sink. Use of evaporative cooling first started in ancient Egypt. Frescoes from about 2500 BC show slaves fanning jars of water to cool them. The vessels were porous enough to maintain wet surfaces to facilitate the process. In Iran, rooms are partially underground to escape solar heat and contain pools of running water with ventilating towers opening above them to catch wind and divert it across the water surfaces below [11]. Evaporative cooling reduces the temperature of incoming air and is generally more efficient where ambient temperature is high and relative humidity (RH) is low. There are two types of evaporative cooling: direct and indirect. In indirect evaporative cooling, evaporation occurs inside a heat exchanger and the water content of the cooled air remains unchanged. Different types of direct evaporative cooling techniques are [12]:

1. Fan and pad evaporative cooling — An exhaust fan is installed at one end of the structure, which pulls air through a wet pad at the opposite end. The pad is essentially a large psychrometer, with maximum cooling dependent upon the wet bulb temperature of the incoming air. It is a very efficient system for hot and dry climates. Use of evaporative cooling pads in greenhouses and in poultry houses is widely accepted in hot regions. The use of evaporative cooling pads can reduce the temperature by 4–13°C [13].

2. Mist propagation (low pressure system) — In mist propagation systems, the canopy is wetted, which maintains a free water surface and actual evapotranspiration equals the potential evapotranspiration. This is still is the development stage and control of RH is more difficult in winter weather conditions [12]. Due to constantly wet conditions, disease may spread inside the greenhouse.

3. Employment of a high pressure system — High pressure systems provide extremely fine mist, essentially allowing a fog that tends to remain in the air. Cooling occurs above the crop with minimal wetting to the foliage. Fog reduces the solar intensity. This system can maintain a more uniform temperature and humidity as compared to the fan and pad system, but this system is expensive, requiring heavy-duty pumps, piping and nozzles, and very clean water; and it has high electrical energy consumption [12,14].

2.2.1. Principle of direct evaporative cooling

The principle of direct evaporative cooling is based on a natural process. Non-saturated air is cooled by exposure to free and colder water. Heat and mass transfer happens as a function of the differences between their respective temperatures and vapour pressures. Water vapour flows away from the higher vapour pressure to the lower vapour pressure side, whereas heat flows from the warmer to the cooler side. Evaporation requires heat absorption. Some of the air's sensible heat transfers to the water and becomes latent heat by evaporating some of the water. As a result, the air temperature falls. Theoretically the process is adiabatic. Heat and vapour exchanges occur until temperatures and vapour pressures equalise. In real cases, there might be two situations [11]: (1) inlet water's entering temperature is in between the dry bulb and wet bulb temperature of the incoming air; for this case heat and the mass transfer phenomenon have been explained above; (2) inlet water's entering temperature exceeds both of these. In this case at first the incoming air absorbs sensible heat from the water and will then follow process (1).

The limit for the direct evaporative cooling is the incoming air's wet bulb temperature; 100% saturation of the incoming air is impossible in a real situation. The reasons for this are: there are unchanged air streams due to the pad geometry which later mixes with the saturated air, and the leakages in greenhouse structures. Also 100% saturation is seldom sought due to the disadvantages such as rusting, warping and mildew of susceptible materials [11]. Efficiency of the evaporative cooling is calculated as

$$E_s = \frac{T_1 - T_2}{T_1 - T_3} \times 100$$

where E_s is the cooling (or saturation) efficiency (%), T_1 the entering air dry-bulb temperature, T_2 the leaving air dry-bulb temperature, and T_3 is the entering air wet-bulb temperature.

2.2.2. Evaporative cooling pads: types and performance

Types and properties of the cooling pad materials have a great impact on the cooling performance and economics. Commercial cellulose paper pads (CELdek) and aspen-wood excelsior pad are generally used in greenhouses. Other types of pad materials have also been demonstrated. Natural fibers such as date palm fibers (stem), jute and luffa were used to test the performance of evaporative cooling [15]. The results were compared against widely used commercial aspen-wood excelsior wetted pad. The performance criteria selected were cooling efficiency, material performance and cooling efficiency degradation with time. It was reported that jute fibers performed well with an efficiency of 62.1% as compared to 49.9% for commercial pads. Material degradation was tested by the salt deposition and bio-degradation technique. The performance degradation of the cooling efficiency was performed by continuously running the test device for 60 h [15]. Due to the high cost of the CELdek pad, alternative materials such as pumice stones, volcanic tuff and greenhouse shading nets were tested and compared for performance against the CELdek [13]. Air velocity, water flow rate and pad thickness were varied to compare performance. It was concluded that volcanic tuff pads can be used as an alternative to CELdeck pads [13].

A performance test of cross-flow evaporative cooling using honeycomb paper pads as packing material was carried out. This type of pad can reduce the air temperature by 9°C and increase the RH by about 50% [16]. A mathematical model was developed, and it was reported that there is an optimum length of the air channel with which a minimum air temperature can be obtained [16]. A down-draft type direct evaporative cooler was developed and tested [17] where the ambient air enters the tower at the top and leaves at the bottom. Different spray (fine/coarse) pattern and air velocitywere adopted to optimise system performance and it was reported that fine spray provided better cooling efficiency. The developed system is capable of decreasing air temperature by 10–15°C at the peak of its performance. Cooling efficiency of 90–95% can be achieved with this type of system [17].

2.3. Proposed design and experiment

Fig. 1 shows the proposed design [6] where the product and concentrate water from an RO system supply a GH with irrigation and cooling water respectively. The reject water from RO is concentrated and reduced in volume, finally to be evaporated to solid in a pond. The solid salt could be disposed of as landfill therefore causing less of pollution than the liquid concentrate [6]. A detailed analysis of the systems components and economical analysis (Table 1) was performed [6].

Pilot experiment — As the objective is to use the plant in arid or semi-arid regions, a fan and pad evaporative cooling technique was selected. The effectiveness or

Table 1
Design parameters of combined PV-RO greenhouse system [6]

Size:	
GH: floor area, m^2	1,000
PV-pump: peak electrical power, W	607
RO membrane: area, m^2	18
GH cooling system: peak air flow, $m^3\ s^{-1}$	35
Well depth, m	10
Water input and output:	
Flow of feed water from well[a], m^3/d	5.4
Salinity of feed water, ppm	5,000
Flow of desalted water for GH irrigation[a], m^3/d	1.8
Salinity of irrigation water, ppm	<500
Flow of concentrate water from RO[a], m^3/d	3.6
Flow of concentrate after volume reduction[a], m^3/d	0.36
Salinity of concentrate after volume reduction[a], ppm	75,000
Costs: (€)	
GH structure	15,000
Desalination system (total), including	8,730
PV-powered pump	7,280
RO membranes	1,450
GH cooling system	12,600
Total	36,330

[a] Annual average.

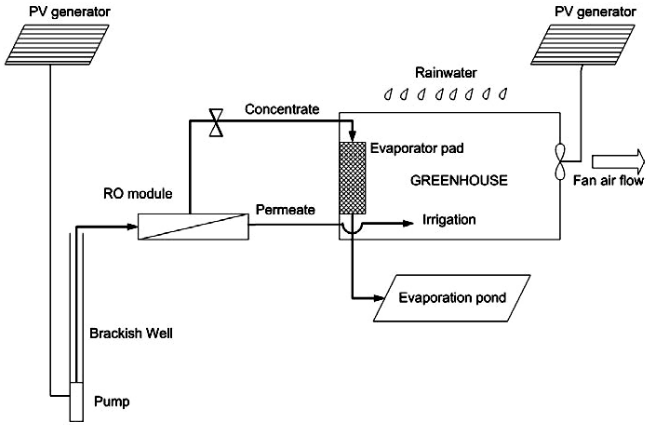

Fig. 1. Design of brackish water desalination system combined with greenhouse cooling (reproduced from [6]).

cooling efficiency of this system varies mainly with the air and water flow rates, water quality, fiber material properties and thickness, ambient temperature and humidity. Two experimental rigs of the same size (3000 × 600 × 300 mm) were constructed to compare the cooling performance of both fresh and salty water side by side. A commercially available CELdek® 7090-15 pad, widely used in greenhouses and livestock buildings, was used in the pilot experiment. The pad consists of specially impregnated and corrugated cellulose paper sheets with different flute angles bonded together to maximise the efficiency while having less scaling and a very low pressure drop.

Feed water is pumped to the top of the cooling pad using a peristaltic pump and is distributed via a manifold. To minimise the water carry-over, water is directed to the air inlet side of the pad where most of the evaporation takes place. The water flows down the corrugated surface of the CELdek pad and part of the water is evaporated by the warm and dry incoming air that passes through the pad and the rest of the water washes the pad; the water is then drained back to the recirculation tank (Fig. 2).

The pilot experiment is considered as a scaled-down version of real greenhouses. The greenhouse has a floor area of 1000 m^2 (Table 1). Quite a typical length for a greenhouse is about 30 m (for longer lengths cooling becomes difficult as the air heats up). This would correspond to a greenhouse about 30 m wide. Cooling pads are normally 1.8 m tall, giving a 54 m^2 face area. But we only have a $0.6 \times 0.3 = 0.18$ m^2 face area. Therefore, our model can be considered as 1/300 scale. Now we should scale flows on the same basis. Note that in the Oxford paper [6], an 8-h day was assumed. So the flow of concentrate water for our rig is 3.6 m^3 per 8-h day/300 = 12 L per 8-h period = 25 ml/min = 0.4 ml/s. Of this we aim to evaporate about 90% i.e. 0.36 ml/s. This is quite a low flow rate.

The air flow and conditions must be adjusted on the basis of mass balance, i.e. the water that evaporates must be taken up by the air. The following calculation is to check that the two match. Now the peak air flow is 35 m^3/s for 1000 m^2 of greenhouse are (Table 1), but the typical flow is $\kappa = 0.55$ times this, or 0.064 m^3/s for our model. This corresponds to 0.36 m/s at the face of the pad.

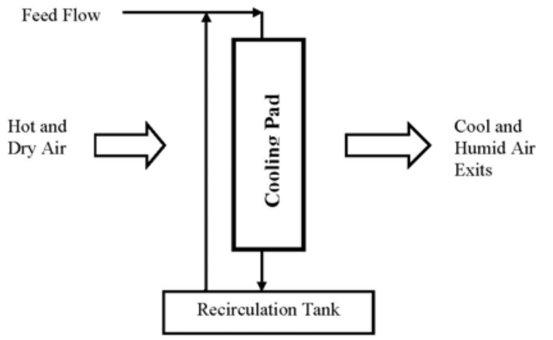

Fig. 2. Feed and recirculation water and air flow.

A typical temperature for an arid region (in Delhi) is about 35° and 30% RH. Using the psychrometric table, such air can absorb $0.8 \times (0.017 - 0.011) = 0.005$ kg/kg of dry air, 0.8 being the effectiveness of the evaporator pad, and 0.011 and 0.017 the specific humidities of the air at outlet and inlet respectively. The specific volume is about 0.89 m^3/kg, corresponding to 0.072 kg/s in the model experiment. So on this basis we can absorb about = 0.072×0.005 kg/s = 3.6×10^{-4} kg/s = 22 ml/min — approximately equal to the 25 ml/min estimated above.

The water composition has been simulated based on typical brackish water composition figures from the Rewari Girls Hostel (Rewari, Haryana, India) area, using NaCl, $NaHCO_3$, Na_2SO_4 and $MgCl_2$. The other ions have been neglected. Note that since the RO plant concentrates the water and a recovery rate of 0.33 has been suggested, this gives a concentration 1.5 times.

In the laboratory, the above settings were simulated for both the fresh water and salt water rigs. An electric heater was used to adjust the incoming air temperature and RH. Air velocity, temperature and RH were measured using Testo® equipment. Feed and recirculation water flow rates were measured manually using a stop watch and funnel. The recirculation flow rate was varied from zero till as required to wet the pad sufficiently.

3. Results

Temperatures and RH of the incoming air, temperature of outgoing air and feed and recirculation flow rates are shown in Table 2. Using these figures cooling efficiencies were calculated and compared. Performance relationships are shown in Figs. 3–5. Initial results show

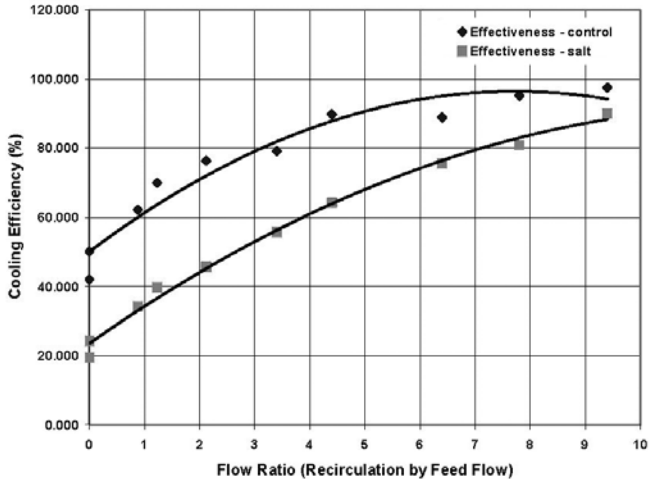

Fig. 3. Cooling efficiency vs. flow ratio of water in evaporative cooling pad inside the greenhouse.

Table 2
Air and water in greenhouse — control system

Incoming air			Outgoing air (Tdb, °C)	Feed flow (ml/min)	Recirculation flow (ml/min)
Tdb (^{0}C)	RH (%)	Twb (^{0}C)			
37.5	42.5	26.5	32.87	26	0
37.77	42.01	26.7	32.22	25	0
39.9	36.67	26.5	31.57	25	22
40.6	36.07	26.7	30.87	26	32
40.43	37.6	27.3	30.4	25	53
39.73	40.37	27.6	30.13	25	85
39.67	40.87	27.8	29.01	25	110
40.03	41.57	28.3	29.6	25	160
39.53	43.57	28.6	29.13	25	195
39.16	44.63	28.3	28.57	25	235

Table 2b
Air and water in greenhouse — salt system

Incoming air			Outgoing air (Tdb, °C)	Feed flow (ml/min)	Recirculation flow (ml/min)
Tdb (^{0}C)	RH (%)	Twb (^{0}C)			
40.57	30.23	25.6	37.65	26	0
36.54	38.77	24.8	33.69	25	0
41.2	30.03	26	36	25	22
40.3	31.93	25.7	34.5	26	32
39.34	37.8	26.8	33.61	25	53
40.8	34.66	27	33.1	25	85
40.6	35.87	27.1	31.93	25	110
41.4	35.33	27.3	30.75	25	160
41.16	36	27.4	30.03	25	195
41.87	35.06	27.7	29.1	25	235

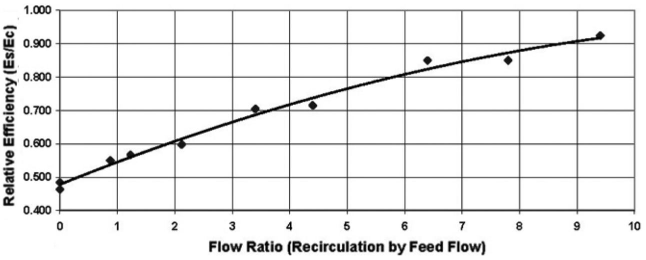

Fig. 4. Relative cooling efficiency vs. flow ratio of water of the evaporative cooling pad in the greenhouse. Es, salt; Ec, control.

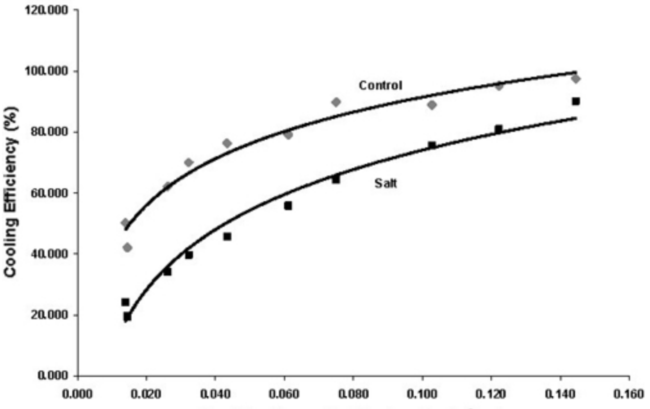

Fig. 5. Cooling efficiency vs. pad top area.

that it is possible to use the RO concentrate for greenhouse cooling purposes. Salt systems provide lower cooling efficiency than the control system (Fig. 3). In the case of salt system, the cooling efficiency increases and reaches close to control system with the increase of recirculation flow (Fig. 3). From this initial experiment, it can be concluded that the volume reduction of the RO concentrate is possible in the combined PV–RO greenhouse system. The pilot experiment shows that a salt deposit in the pad occurred (Fig. 6), but did not affect the cooling efficiency. However, experiments should be conducted for long hours before reaching any such conclusion. The salt

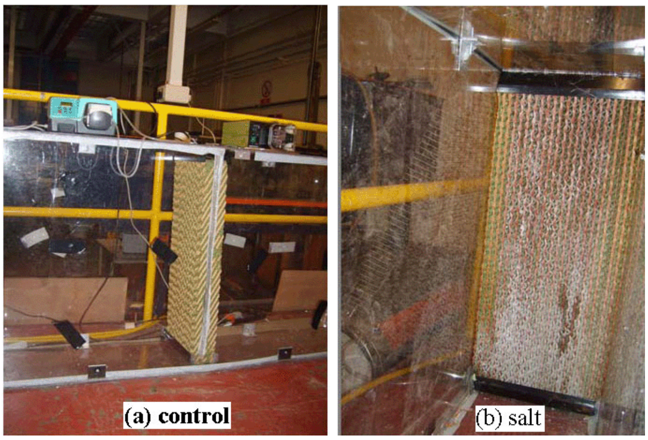

Fig. 6. Cooling pads: control and salt system

and control system experiments were conducted on different days (different ambient conditions). Conducting the tests simultaneously on the same day would help to get a better comparison.

4. Conclusions and future work

The evaporative cooling system cools incoming air near to the outside wet bulb temperature. Another advantage of evaporative cooling is the reduction of air vapour pressure deficit, which reduces water stress in the plant [18]. Evaporative cooling is standard practice; however, salty water is not normally used. A system has been tested in which concentrate from RO is disposed of by evaporation, at the same time providing cooling to a greenhouse. Initial test results show that RO concentrate can be managed economically and sustainably in this way.

However, greenhouse cooling requirements vary greatly depending upon the crop grown and the ambient condition. However, for crops needing low temperatures and low humidity, then a mechanical air conditioning system is the most suitable option.

Results show good cooling efficiency of the salt systems compared to the control (reference) system. As the recirculation rate increases, the cooling efficiency of the salt system increases and closely approaches the control system. Thus, it can be concluded that the reduction of RO concentrate volume is possible, which help to manage the RO concentrate in economic and sustainable ways.

Future studies to be carried out are: (1) test both rigs simultaneously for a certain number of hours and examine the material performance, cooling efficiency degradation and salt deposit with time; (2) test the cooling performance with other inexpensive and environmentally friendly pad materials with different thicknesses; (3) test performance by varying air velocity, ambient conditions and salt composition; (4) test and examine the case of salt carry-over inside the greenhouse; and (6) build the whole test rig—including the RO module and pump—and compare the performance.

Acknowledgements

The authors acknowledge funding from the UK Engineering and Physical Sciences Research Council, grant reference EP/E044360/1.

References

[1] E. Kondili and J.K. Kaldellis, Wind energy based desalination process and plants. Proc. World Renewable Energy Congress (WRECX), WREC, Glasgow, UK, 2008.

[2] E.S. Hrayshat, Brackish water desalination by a stand alone reverse osmosis desalination unit powered by photovoltaic solar energy. Renewable Energy, 33 (2008) 1784–1790.

[3] J.G. McGowan and J.F. Manwell, Techno-economic feasibility study of wind-powered desalination for community scale distributed generation application. Proc. World Renewable Energy Congress (WRECX), WREC, Glasgow, UK, 2008.

[4] G.E. Ahmed and J. Schmid, Feasibility study of brackish water desalination in the Egyptian deserts and rural regions using PV systems. Energy Conv. Manage., 43 (2002) 2641–2649.

[5] M. Thomson and D. Infield, Laboratory demonstration of a photovoltaic-powered seawater-osmosis system without batteries. Desalination, 183 (2005) 105–111.

[6] P.A. Davies, A.K. Hossain and P. Vasudevan, Stand-alone groundwater desalination system using reverse osmosis combined with a cooled greenhouse for use in arid and semi-arid zones of India, Desal. Wat. Treat., in press.

[7] P.A. Davies and C. Paton, The Seawater Greenhouse in the United Arab Emirates: thermal modelling and evaluation of design options. Desalination, 173 (2005) 103–111.

[8] A. Raoueche and B.J. Bailey, Performance aspects of a seawater greenhouse. 23rd WEDC Conference, Water and Sanitation for all: Partnerships and Innovations, Durban, South Africa, 1997.

[9] A. Raoueche, B. Bailey and B. Stenning, Sensitivity analysis of the seawater greenhouse. 22nd WEDC conference, Sensitivity Analysis of the Seawater Greenhouse, New Delhi, India, 1996.

[10] M. Wilf, The Guidebook to Membrane Desalination Technology. Balaban Desalination Publications, Italy, 2007.

[11] J.R. Watt and W.K. Brown, Evaporative Air Conditioning Handbook, 3rd ed., Fairmont Press, USA, 1997.

[12] J.J. Hanan, Greenhouses – Advanced Technology for Protected Horticulture, CRC Press, Boca Raton, FL, 1998.

[13] T. Gunham, V. Demir and A.K. Yagcioglu, Evaluation of the suitability of some local materials as cooling pads. Biosys. Eng., 96(3) (2007) 369–377.

[14] R.A. Bucklin, J.D. Leary, D.B. McConnell and E.G. Wilderson, Fan and pad greenhouse evaporative cooling systems. Circular 1135, Institute of Food and Agricultural Sciences, University of Florida, USA, 2004.

[15] F. Al-Sulaiman, Evaluation of the performance of local fibers in evaporative cooling. Energy Conv. Manage., 43 (2002) 2267–2273.

[16] Y.J. Dai and K. Sumathy, Theoretical study on a cross-flow direct evaporative cooler using honeycomb paper as packing material. Appl. Thermal Eng., 22 (2002) 1417–1430.

[17] D. Pearlmutter, E. Erell, Y. Etzion, I.A. Meir and H. Di, Refining the use of evaporation in an experimental down-draft cool tower. Energy Build., 23 (1996) 191–197.

[18] Argus, Cooling System Design Guidelines. http://www.arguscontrol.com/articles (accessed 23 September 2008).