Development of Sustainable Farming Compartment with Treated Wastewater in Abu Dhabi

Jongwan Eun, Sam Helwany, Lakshyana K. C.

Abstract**—**The United Arab Emirates (UAE) is significantly dependent on desalinated water and groundwater resource, which is expensive and highly energy intensive. Despite the scarce water resource, stagnates only 54% of the recycled water was reused in 2012, and due to the lack of infrastructure to reuse the recycled water, the portion is expected to decrease with growing water usage. In this study, an "Oasis" complex comprised of Sustainable Farming Compartments (SFC) was proposed for reusing treated wastewater. The wastewater is used to decrease the ambient temperature of the SFC via an evaporative cooler. The SFC prototype was designed, built, and tested in an environmentally controlled laboratory and field site to evaluate the feasibility and effectiveness of the SFC subjected to various climatic conditions in Abu Dhabi. Based on the experimental results, the temperature drop achieved in the SFC in the laboratory and field site were5℃ from 22℃ and 7- 15℃ (from 33-45℃ to average 28℃ at relative humidity < 50%), respectively. An energy simulation using TRNSYS was performed to extend and validate the results obtained from the experiment. The results from the energy simulation and experiments show statistically close agreement. The total power consumption of the SFC system was approximately three and a half times lower than that of an electrical air conditioner. Therefore, by using treated wastewater, the SFC has a promising prospect to solve Abu Dhabi's ecological concern related to desertification and wind erosion.

Keywords**—**Ecological farming system, energy simulation, evaporative cooling system, treated wastewater, temperature, humidity.

I. Introduction

DESERTIFICATION is one of the major ecological problems facing the Arabian Peninsula region. In spite of the national, regional and internationally collaborated efforts for combating desertification and mitigating the effect of drought and desiccation, desertification is still one of the major environmental issues in the region [1]. In the UAE, wind erosion is one of the major contributors to land degradation due to the prevailing hyper-arid conditions, poor vegetation cover, and strong wind [2], [3]. With the removal of the fertile top soil by erosion, the desertification process is readily progressed and accelerated [3]. Therefore, it is important to minimize the wind erosion and so as to mitigate the problem of desertification.

The UAE is characterized by a hyper-arid climate with less than 120 mm of average annual rainfall [4]. The UAE is significantly dependent on groundwater resource and desalinated water, which is very expensive and highly energy intensive. Despite the scarcity of water resource, only 54% of the treated wastewater was reused in 2012 and the remaining 48% was thrown back into the ocean in Abu Dhabi [5]. Moreover, the production of the wastewater is expected to continuously increase by 10% until 2030 with the resulting increase in total water production from due to the development of the urban area, increasing population, and the enhancement of life quality in Abu Dhabi [6]. To resolve this situation, the Abu Dhabi government ambitiously intends to reuse 100% of its wastewater by 2030 [5], [6]. However, the main challenge underlying complete utilization of treated wastewater is the underdeveloped distribution system [5]. Currently, the treated wastewater is used mostly for irrigation of public parks and roadsides and for district cooling in residential areas, but this consumption does not meet the production of the water [5]. Hence, the development of method for better utilization of the treated wastewater is a warrant to increase the recycling rate of the water in the region.

In this study, the "Oasis" complex comprised of SFCs in using treated wastewater was introduced to increase the recycling rate of water as well as to mitigate desertification and wind erosion. To verify the effectiveness and the feasibility of the concept of the "Oasis" complex and the SFC, an experiment, comprising of an SFC prototype, with half the scale of the actual structure, was developed and tested. The temperature and humidity were monitored during the test in both environmentally controlled and field conditions. Energy simulation via TRANSYS was also performed to evaluate the heat transfer in the SFC and to validate the experimental results.

II. Background

A. The "Oasis" Complex

Based on two main motivations for this study, which are the environmental issue related to serious desertification in the UAE and the plan to increase of utilizing recycling water, two main goals can be derived. The first is to manage wind erosion to minimize the process of desertification. Another is to develop a sustainable mechanism for utilizing treated wastewater, such as cultivation of selected plants under favorable conditions. To fulfill these goals, the concept of the "Oasis" complex is newly introduced (Fig. 1) by the authors.

The "Oasis" concept is based on the integration of innovative ideas and sustainable methods for farming to achieve those goals. The "Oasis" complex is composed of SFCs and protected zones. To utilize treated wastewater, the "Oasis" complex is

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going to be constructed in the vicinity of wastewater treatment plants for its easy access. A long chain of the SFCs surround the perimeter of the "Oasis" complex. The SFC, which is made of structures designed to withstand the wind loads, can act as a protective fence against wind erosion while at the same time accommodating crops that require lower temperatures for optimal growth. Therefore, this is an effective alternative to combat desertification and to utilize recycled water in the UAE.

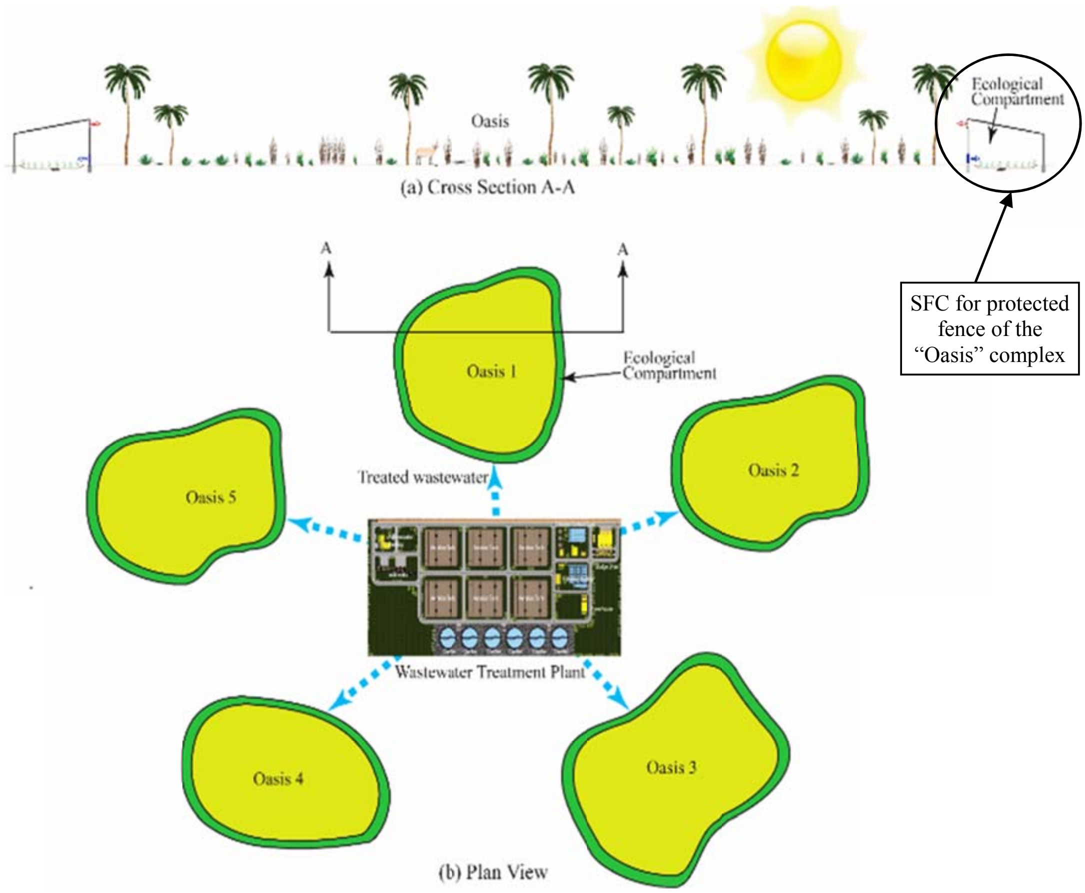

Fig. 1 The concept of the "Oasis" complex in the vicinity of Wastewater Treatment Plants

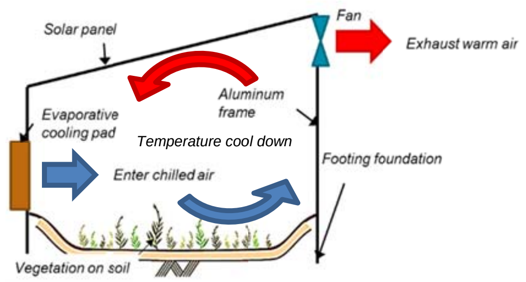

Fig. 2 SFC and its principle to reduce the inside temperature

B. SFC

The SFC was designed to install exhaust fans and an evaporative cooling system by using treated wastewater to decrease the inside temperature. The agricultural plants can be raised in the compartment even during hot-dry weather outside by maintaining a relatively low temperature inside. Hence, the SFC requires the preliminary investigation in the environmentally controlled laboratory and field site to evaluate the feasibility and effectiveness of the SFC subjected to the actual climatic conditions in Abu Dhabi. Potentially, the electricity generated from solar panel installed on the roof will be used for running the system so as to make it self-sufficient.

C. Evaporative Cooling System

The SFC includes an evaporative cooling system by using treated wastewater to decrease the inside temperature. The evaporative cooling system was designed to lower the temperature inside through the absorption of the latent heat by the evaporating water. The temperature of dry air can be dropped significantly through the phase transition of liquid water to water vapor (evaporation), which can cool air using much less energy than refrigeration [7], 8]. The cooling potential for evaporative cooling is dependent on the wet bulb depression, the difference between dry-bulb temperature, and the wet-bulb temperature described by the psychrometric chart. In the process, the humidity is important [9], [10].

III. Experimental Program

A. Prototype SFC

The prototype SFC was built using aluminum frames (40×40 mm) provided by 80/20 Material Inc. The material can be readily assembled with only mechanical bonding. The stability of the structure was confirmed by the SAP 2000 analysis. The dimension of the SFC used was 1.8 m of width, 1.5 m of depth, 1.2 m of the front height, and 0.9 m of the back height, which is half the scale of the actual structure. The bottom is composed of plywood and the walls were composed of Plexiglas panels, with approximately three to five times lower thermal conductivity (= 0.2 $W^{-1}\cdot m^{-1}\cdot K$) in comparison to glass. The roof was covered by polystyrene sheet to reduce direct heat exchange during the test. On the upper wall of the front side, five exhaust fans were installed, with performance of 190 CFM per fan. On the back side, a cardboard cooling pad (0.1 × 0.45 × 1.8 m) was installed for the evaporative cooling system. To monitor the variation of temperature and humidity for the inside and outside during the test, two portable sensors with 12-bit resolution were installed. The resolution of the temperature and humidity is 0.3℃ and 0.03%, respectively. The accuracy is ± 0.35℃ for temperature and ± 2.5% typical for humidity. The data was collected every minute for 3 days.

For the water supplying system, 30 mm-PVC pipes and upper and lower water reservoirs were installed. The volume of each water reservoir is approximately 0.12 m^3. The water flow rate can be controlled by the valve at the pipe. Tap water was used for the test and distributed equivalently to the pad from the upper reservoir. The water pump was installed to circulate and reuse the water from the pad to the upper reservoir in the system.

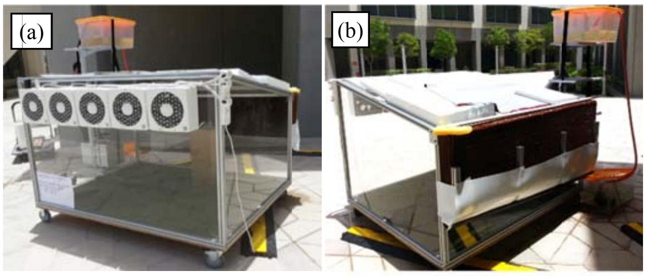

Fig. 3 Photo of prototype setup for SFC: (a) Front view with exhaust fans and (b) Back view with evaporative cooling pad and water supply system

B. Initial Conditions for SFC Test

The water for initially saturating the pad is 8 L. The flow rate of the water supply system is approximately 500 cm^3/s. The hydraulic gradient to supply water from the upper reservoir to the distribution system is 0.5 (m/m).

C. Preliminary Test in Controlled Condition in Laboratory

To examine the performance of an exhaust fan and evaporative cooling pad in environmentally controlled condition, a preliminary test using only the fan and the pad was conducted. In the controlled volume, the evaporative cooling system was run and the variation of temperature and humidity inside and outside was monitored simultaneously. The polyethylene chamber (0.45 × 0.45 × 0.9 m) was used for the controlled volume to minimize heat transfer during the test. Two fans and evaporative cooling pad (0.3 × 0.45 × 0.9 m) were used as they were sufficient to cover the entire box. The results of the test were compared to the values provided from the psychrometric chart. The room temperature and the relative humidity in the laboratory were consistently 22℃ and 60%, respectively.

IV. Energy Simulation

Energy simulation was performed to evaluate the heat transfer in the SFC and to validate the experimental results. For the simulation, TRNSYS 17 was used, which is a simulation program typically used in the fields of renewable energy and building simulation. In this study, the prototype SFC including exhaust fans and evaporative cooler subjected to actual weather data of the UAE was modeled. All materials were identical to those used during the prototype test. The input parameters to define the simulation are summarized in Table I. The data of the simulation was collected every minute for one week after stabilizing the data. The boundary condition is constant heat flow rate and there is no heat loss from absorption in the material.

TABLE I
Material Properties for Energy Simulation by TRNSYS 17

Type	Material	Thermal Conductivity $W^{-1}\cdot m^{-1}\cdot K$
Frame	Aluminum	101.8
Wall	Plexiglass	0.2
Bottom	Plywood	0.16
Roof	Plexiglass	0.2
	Styrene sheet	0.033

V. Results and Discussions

A. Monitored Temperature and Humidity in Controlled Condition in Laboratory

Fig. 4 shows the results of the environmentally controlled condition. The temperature and humidity inside and outside the chamber were monitored for one hour. The temperature at the inside chamber during the test dropped from 22℃ to 17℃, which is 5℃ difference compared to room temperature. According to psychometric chart at given initial condition, temperature drop is 5.5℃ from 22℃ to 16.5℃, which is almost identical to the results of the test. Relative humidity at the inside chamber increased significantly from 60% to 90% during the test. The maximum was 95%. Typically, the temperature in the chamber decreased with increasing the relative humidity. This is because latent heat as evaporation proceeded in the pad took out the heat and the temperature was dropped. Water consumption was approximately 4 L during the test. The stabilization of temperature and relative humidity occurred around 50 and 30 minutes later, respectively.

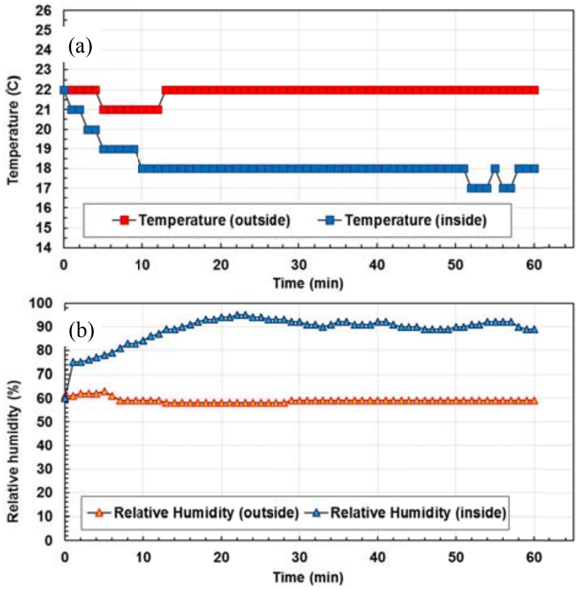

Fig. 4 Variation of temperature and humidity in environmentally controlled condition in laboratory: (a) Temperature and (b) Humidity

B. Monitored Temperature and Humidity during the Test

The prototype SFC test was conducted at the campus of NYUAD during the first week of May. Fig. 5 demonstrates the temperature and humidity monitored in the SFC test for 3 days. The temperature outside ranged from 25.7℃ to 55.6℃. The average and difference in the temperature between the highest and lowest were 32.2℃ and 29.9℃, respectively. The temperature inside in the compartment is ranged from 22.5℃ to 34.9℃. The average and difference of the temperature between the highest and lowest are 26.4℃ and 12.3℃, respectively.

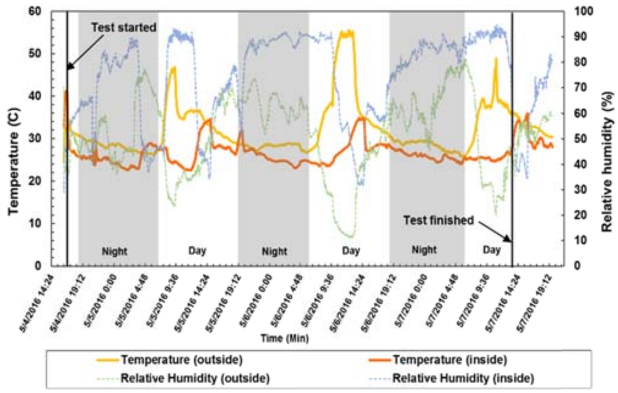

Fig. 5 Variation of temperature and humidity for prototype SFC test for 3 days in May

The outside relative humidity of ranged from 11% to 81%. The average and standard deviation of the temperature are 51% and 16%, respectively. The inside relative humidity ranged from 31% to 94%. The average and standard division of the temperature are 74% and 17%, respectively. As the humidity increases, the temperature decreases in the compartment. On the contrary, the temperature increases with reduced humidity. The trend between the humidity and the temperature in the compartment was totally inverse during the test. The variation of temperature outside and humidity inside was higher than that of the temperature inside and humidity outside. The inside temperature was mostly maintained under 28℃ except the peak time of temperature outside from Noon to 2 PM.

Three unexpected peaks of the temperature inside the compartment might be due to running out of the water to be supplied to the evaporative cooling system. The water running out can be observed by the sharp drop of the humidity inside the compartment.

C. Comparison of Data between Experiment and Simulation

Fig. 6 shows the comparison of temperature and humidity obtained from the experimental tests and energy simulation by TRNSYS. The average temperature and humidity obtained from TRNSYS are 26℃ and 78%, respectively. The results show statistically no difference from the T-test ($p = 0.09 > 0.05$). The difference between the average data is 0.4℃ for the temperature and 3.5% for the humidity.

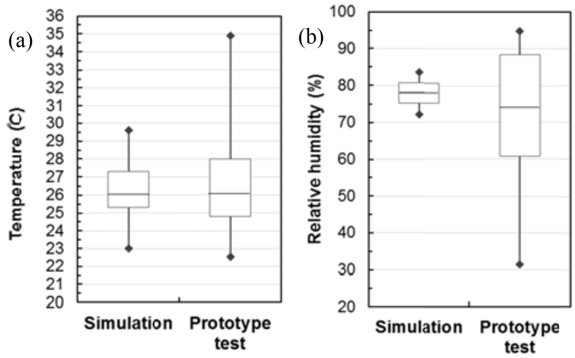

Fig. 6 Comparison of temperature and humidity between simulation by TRNSYS and prototype test: (a) Temperature and (b) Humidity

D. Electricity and Water Consumption

The electricity and water consumption were measured during the test to evaluate the consumption of the electricity and water from the SFC. The electricity consumed to run the SFC was compared to that to cool down the identical condition of the compartment by Air Conditioner (AC) with compressor. The typical AC requires 5300 W·h for 1.5 tons and 18000 BTU/hour according to the manual of AC [7]. The SFC used in the study is about 0.25 tons. Therefore, the SFC system by running the AC requires 830 W per one hour. However, the SFC system by running evaporative cooling system including five fans and water pump used in this study consumed only 260 W per hour, which is almost three and half times lower than that of typical AC system. Fig. 7 shows the comparison of electricity consumption and cost between the system of this study and typical AC to cool down the temperature of the prototype SFC used in the study. Both of the electricity consumption and cost for evaporative cooling system is significantly lower than those for AC.

During the test, 132 L of the tap water was consumed per day and per area of the cooling pad. If the treated wastewater is used for field compartment system having approximately eight times larger volume than the prototype SFC in the study, 1060 L water will be consumed in a day assuming that the environmental condition is identical to the testing condition in the study. Therefore, for rough calculation to extend to the "Oasis" complex, one complex will consume approximately 12000 L per day and 3.6-Million Liter per year. This might be beneficial to increase the recycling rate of treated wastewater in Abu Dhabi.

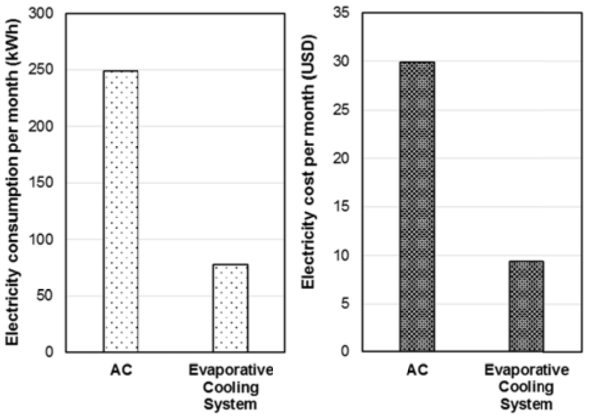

Fig. 7 Comparison of electricity consumption and cost per month (the average cost is 12 cents per watt in US) between typical AC with compressor and evaporative cooling system to cool down the temperature of the prototype SFC used in the study: (a) Electricity consumption and (b) Electricity cost (USD)

VI. Conclusion and Expectation

In this study, the concept of the "Oasis" complex comprising of the SFC and protected zone, which make use of the treated wastewater, was proposed to increase the recycling rate of the water as well as to mitigate desertification and wind erosion, which are major concerns for the UAE's environment and ecological system. The wastewater can be used to decrease the ambient temperature of the SFC via an evaporative cooler. Prototype SFC was designed, built, and tested in the environmentally controlled laboratory and field site to evaluate the feasibility and effectiveness of the SFC subjected to actual climate conditions in Abu Dhabi. Based on the experimental results, the temperature drop achieved in the SFC in the laboratory and field site were 5℃ (from 22℃) and 7- 15 ℃ (from 33-45℃) respectively, reaching an average temperature of 28℃ (at relative humidity < 50%). Both experimental results coincided with the results from psychrometric chart. Energy simulation by using TRNSYS was also performed to extend and validate the results obtained from the experiment. The results between the energy simulation and experiments show statistically no difference (T-test $p = 0.09 > 0.05$).

The total power consumption of the SFC system was about 260 W per hour, which is approximately three and a half times lower than that of an air-conditioning system for cooling off the compartment. During the test, 132 L of tap water was consumed per day and per area of the cooling pad. If the treated wastewater is used for field compartment system, 1060 L water will be consumed in a day, assuming an identical testing condition in the study.

Overall, this project could be considered to be a success as it was able to achieve the goal that it had initially set out to achieve and it fulfills most of the design and evaluation criteria for testing for the proof of concept. If the research is successfully completed, the outcome will promise the validation of "Oasis" complex and SFC by using treated wastewater for combating desertification. Moreover, the recycling rate of water will increase to enhance the sustainability of the UAE. Based on the research, there is a potential for extending this research to collaborate with other areas such as mechanical, biological, and agricultural engineering in the Gulf Cooperation Council (GCC). Further, the oasis sector developed can be a great educational place to demonstrate the "green concept" and sustainability practices for students and the public.

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