Article

Energy-Based Performance Analysis of a Sustainable Farming Compartment with Evaporative Cooling System

M. Sina Mousavi [1], Siamak Mirfendereski [2], Jae Sung Park [3] and Jongwan Eun [4,*]

[1] Department of Civil Engineering, University of Nebraska-Lincoln, Omaha, NE 402480-2150; sina.mousavi@huskers.unl.edu
[2] Department of Mechanical and Materials Engineering, University of Nebraska-Lincoln, Lincoln, NE 68588-0526; e-mail: siamak.mir@huskers.unl.edu
[3] Department of Mechanical and Materials Engineering, University of Nebraska-Lincoln, Lincoln, NE 68588-0526; e-mail: jaesung.park@unl.edu
[4] Department of Civil Engineering, University of Nebraska-Lincoln, Omaha, NE 402554-3544; e-mail: jeun2@unl.edu
* Correspondence: jeun2@unl.edu; Tel.: +1-402-554-3544

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, only 54% of the recycled water was reused in 2015. In this study, an "Oasis" complex comprised of Sustainable Farming Compartments (SFCs) was proposed for reusing treated wastewater to decrease the ambient temperature of the SFC via an evaporative cooling system. A prototype SFC with half the original scale (width = 1.8 m, depth = 1.5 m, front height = 1.2 m back height = 0.9 m) was designed, built, and tested in an environmentally controlled laboratory and field site to evaluate the feasibility and effectiveness of the SFC under the climatic conditions in Abu Dhabi. Based on the experimental results, the temperature drops obtained from the SFC in the laboratory and field site were 5℃ at initial relative humidity of 60% and 7- 15℃ at initial relative humidity of 50%, respectively. An energy simulation using dynamic numerical simulations was performed in comparison to the results of the experiment. The energy-based dynamic simulation shows good agreement with the experimental results. The total power consumption of the SFC system was approximately three and a half times lower than that of an electrical air conditioner.

Keywords: Ecological farming system, dynamic numerical simulation, evaporative cooling system, treated wastewater, temperature, humidity

1. Introduction

Desertification, which is a process of the land degradation becoming dessert, is one of the major environmental 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, 2]. 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 [3, 4]. For instance, as the fertile topsoil can be removed by wind erosion, the desertification process is readily progressed and accelerated [4, 5]. Therefore, it is significantly 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 [6]. 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%

 doi:10.20944/preprints201805.0041.v1

of the treated wastewater was reused in 2015 and the remaining 48% was thrown back into the ocean in Abu Dhabi [7]. Moreover, the production of the wastewater is expected to continuously increase by 10% until 2030 with the resulting increase in total water production due to the development of the urban area, increasing population, and the enhancement of life quality in Abu Dhabi [8]. To resolve this situation, the Abu Dhabi government ambitiously intends to reuse 100% of its wastewater by 2030 [7, 8]. However, the main challenge underlying complete utilization of treated wastewater is the underdeveloped distribution system [7]. Currently, the treated wastewater is mostly used 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 [7]. Hence, the development of a method for better utilization of the treated wastewater is a warrant to increase the recycling rate of the water in the region.

Recently, the sustainable agricultural complex was proposed [8] as an alternative method to mitigate desertification and wind erosion as well as to increase the recycling rate. The complex is expected to decrease the temperature inside the structure by using renewable energy such as evaporative cooling system and solar panels with the treated wastewater so that plants and crops are raised. In this study, to investigate the effectiveness and the feasibility of the Sustainable Farming Compartments (SFC) composed of an "Oasis" complex in the UAE, a prototype SFC with half the scale of the actual structure was designed, built, and tested. The temperature and humidity in the SFC, as well as climate conditions in outside, were monitored during the test in both environmentally controlled and field conditions in summer. In addition, an energy simulation via dynamic numerical simulations of the SFC was conducted to evaluate the heat transfer and stabilization in the SFC and to compare with the experimental results. The energy-based performance of the SFC was evaluated based on the results to assess the effectiveness and the feasibility of the SFC.

1.1. 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 utilizing recycling water, two main goals can be derived. First is to manage wind erosion to minimize the process of desertification. The other 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 was introduced as shown in Figure 1.

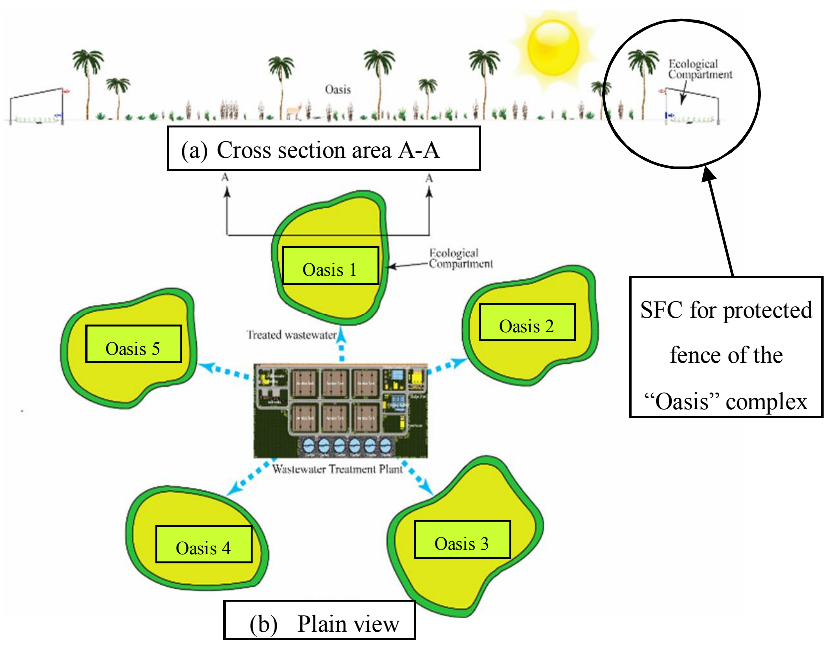


Figure 1. The concept of the "Oasis" complex in the vicinity of wastewater treatment plants.

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 going to be constructed in the vicinity of wastewater treatment plants for its easy access. A long chain of the SFCs surrounds 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.

1.2. Sustainable Farming Compartment (SFC)

The SFC is designed to install exhaust fans and an evaporative cooling system by using treated wastewater to decrease the inside temperature as shown in Figure. 2. Selected agricultural plants such as cucumber and maize can be raised in the compartment even during hot-dry weather outside by maintaining a relatively low temperature inside [9]. 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.

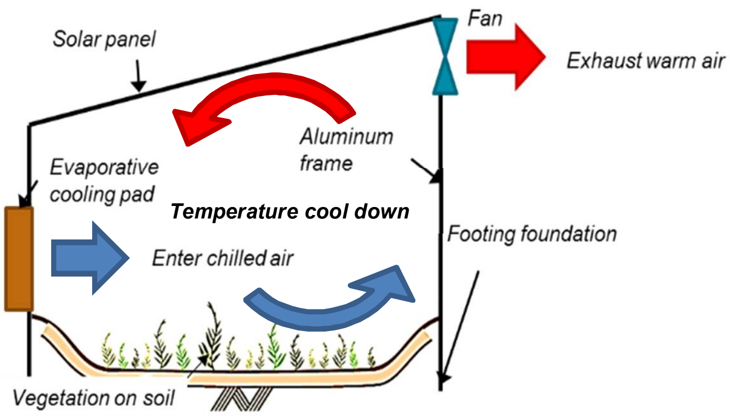


Figure. 2. Sustainable Farming Compartment (SFC) and its principle to reduce the inside temperature.

1.3. Evaporative Cooling System

The SFC includes a direct 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 from liquid water to water vapor (evaporation), which can cool air using much less energy than refrigeration [10,11,12]. 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 SFC system, the humidity is important [13, 14]. In the direct evaporative cooling system, the relative humidity is increased because of air coming into direct contact with water of the cooling pad and its vaporization. Accordingly, the temperature in the compartment will not decrease when the humidity theoretically reaches 100 %, but practically, the temperature does not decrease when the humidity reaches around 85% [15]. Therefore, it is important to monitor the variations of humidity to analyze the process and compare the results with the chart.

Many studies have been conducted to investigate the performance of evaporative cooling systems. Ibrahim et al. achieved the drop of 6-8 °C dry bulb temperature with 30% increase in relative humidity using direct evaporative cooling system supported by porous ceramics in Nottingham [15].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 May 2018 doi:10.20944/preprints201805.0041.v1

Lertsatitthanakorn et al. studied the effect of a 1.8 m by 3.6 m direct evaporative cooling pad in a 32-m^2 silkworm-rearing house in Maha Sarakham, Thailand. Their results show that 6-13 °C dry bulb temperature decreases with increasing 30-40% relative humidity. Further economic analysis showed a 2.5-year payback period for this system indicating its cost-effectiveness [16]. Heidarinejad et al. provided a two-stage indirect/direct evaporative cooling system experiment in various climate conditions in Iran. They showed that in regions with high wet bulb temperature this system can be used instead of mechanical vapor compressions with one-third of their energy consumption. Their results also show that the two-stage system has 55% more water consumption than a direct evaporative cooling system that favors the later system in arid areas [17]. Recently, Aljubury and Ridha conducted a two-stage indirect/direct evaporative system using groundwater to study its effect on the greenhouse in Iraq desert climate. The results show 12.1-21.6 °C decrease in temperature and increase of relative humidity from 8% to 62% compared to ambient condition [18].

2. Materials and Methods

2.1. Experimental Program

2.1.1. Prototype SFC

The prototype SFC was built using aluminum frames (40 × 40 mm) provided by 80/20 Material Inc (Figure. 3). The material can be readily assembled with only mechanical bonding to have enough stability of the structure. 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 $W^{-1} m^{-1} K$) in comparison to glass. The roof was covered with white color-polystyrene insulated sheet (the thickness = 0.05 m) to reduce direct solar radiation through the compartment to generate heat exchange during the test. On the upper wall of the front side, five exhaust fans were installed, with the 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 of the inside and outside during the test, four portable sensors with 12-bit resolution were installed at the center of the compartment and outside roof and ambient outside near the SFC, respectively. The resolution of the temperature and humidity is 0.5℃ and 0.05%, respectively. The accuracy is ± 0.5℃ for temperature and typically ± 2.5% for humidity. The data was collected every minute. The SFC was placed near outside campus of NYUAD during the test, which is typical weather condition of the UAE.

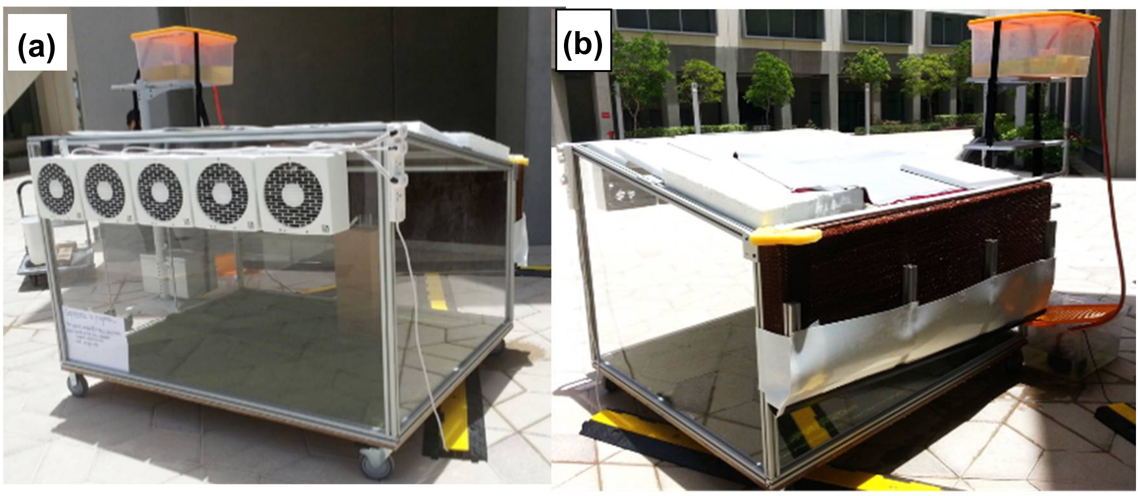


Figure. 3. Photo of prototype setup for SFC: (a) Front view with exhaust fans and (b) Back view with evaporative cooling pad and water supply system.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 May 2018 doi:10.20944/preprints201805.0041.v1

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.

2.1.2 Initial Conditions for SFC Test

The water used for initially saturating the pad is 10 L. The flow rate of the water supply system is approximately 5 L/hr. The hydraulic gradient to supply water from the upper reservoir to the distribution system is 0.5 (m/m).

2.1.3 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 minimal gap between the fans and box was sealed with silicone sealant. The results of the test were compared to the values provided by the psychrometric chart. The room temperature and the relative humidity in the laboratory obtained from two portable sensors, which is the same for the prototype test, were consistently 22.0℃ and 60%, respectively.

2.2. Dynamic Numberical Simulation of SFC

For dynamic numerical simulations of the SFC system, the in-house numerical code was developed to evaluate the thermal performance of the SFC and to validate the experimental results. For simulations, 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 material properties used as input parameters to define the simulation are summarized in Table 1. The physical system upon which the numerical simulation is based is shown schematically in Figure. 4. Boundary conditions at both side walls of the SFC and the roof are constant temperature, which might be conservative. No heat flux is set at the bottom.

Table 1. Material Properties for Energy Simulation

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

2.2.1 Governing Equations of Mathematical Model

The model is based on the conservation of mass, momentum, and energy. An incompressible fluid in a two-dimensional (2-D) domain with a trapezoidal geometry with the same size of the experimental prototype was prepared as shown in Fig. 4. The actual SFC is designed as a plain strain condition (e.g., a long chain), which is close to the model of 2-D domain.

The characteristic length and velocity scales are Lc = Ac/P and the velocity of the exhaust fan Uc, where Ac and P is the area and perimeter of the trapezoidal geometry, respectively. With these

 doi:10.20944/preprints201805.0041.v1

characteristic scales, the conservation equations for momentum, mass, and energy in non-dimensional form are

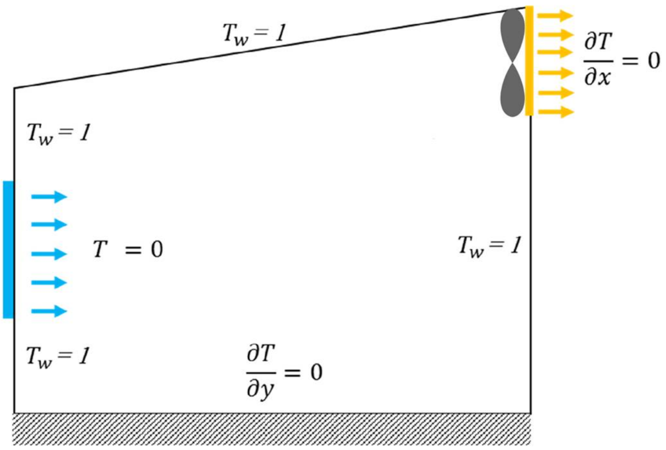


Figure. 4. System schematic of the simulation model

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial P}{\partial x} + \frac{1}{Re}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{1}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial P}{\partial y} + \frac{1}{Re}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{3}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{1}{RePr}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

where the Equations (1) – (3) are indeed the Navier-Stokes equations. Here, we define the Reynolds number and the Prandtl number as Re = UcLc/ν and Pr = ν/α, respectively, where ν is the kinematic viscosity of the fluid and α is the thermal diffusivity of the fluid. For boundary conditions, a no-slip boundary condition was assumed at the walls in the momentum equation. The constant velocity was assumed at the outlet due to the exhaust fan, while Neumann inflow condition was applied for the evaporative cooling system. In the energy equation, a uniform temperature is assumed at the side walls and the roof. Cold air of a uniform temperature was injected through the evaporative cooling system. Neumann boundary conditions for outflow of the temperature are used due to the exhaust fan. No heat flux condition was considered for the bottom floor.

2.2.2 Numerical Method

In the current simulation, a boundary-fitted grid system is created for the trapezoidal space, and then the governing equations are transformed for a rectangular computational domain using 2×2 Jacobean matrix [19]. A staggered grid system was generated to solve the two-dimensional governing equations and a second-order explicit finite difference method (center in space and forward in time) was used for discretization of the equations [20, 21]. A fractional-step method or the projection algorithm was employed for the calculation of velocity field [22, 23]. In this algorithm, the intermediate velocity in Equation (5) is defined to split the momentum equation. With the continuity equation, the Poisson equation in Equation (6) was solved via Successive Over Relaxed (SOR) method to correct the intermediate velocity to satisfy the divergence restraint on the velocity field. The energy equation in Equation (8) was solved using a second-order explicit finite difference method to calculate the temperature field.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 May 2018 doi:10.20944/preprints201805.0041.v1

$$\frac{V^{*}-V^{n}}{\Delta t}+[(V.\nabla)V]^{n}=\frac{1}{Re}\nabla^{2}V^{n} \quad (5)$$

$$\nabla^{2}P^{n+1}=\frac{\nabla.V^{*}}{\Delta t} \quad (6)$$

$$\frac{V^{n+1}-V^{*}}{\Delta t}+\nabla P^{n+1}=0 \quad (7)$$

$$\frac{T^{n+1}-T^{n}}{\Delta t}+[(V.\nabla)T]^{n}=\frac{1}{RePr}\nabla^{2}T^{n} \quad (8)$$

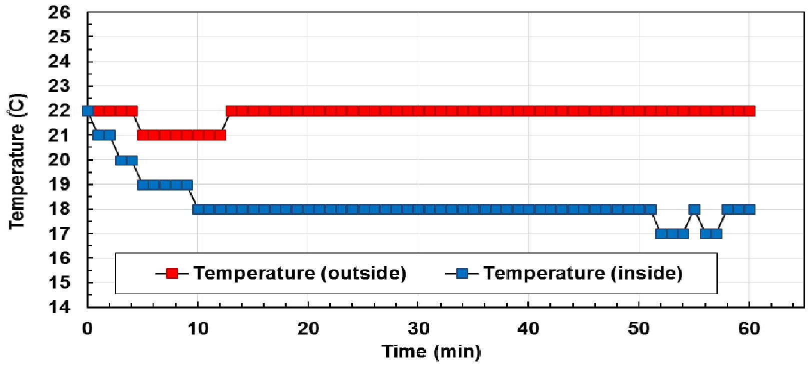
All computation performed on 192×192 mesh and the time step (Δt) was in order of 10^{-5} to insure the numerical stability condition. The tolerances used in the simulation as stopping criterions were respectively 10^{-8} and 10^{-10} for velocity and temperature computations.

3. Results

3.1. Monitored Temperature and Humidity in Controlled Condition in Laboratory

Figure. 5 shows the results of the environmentally controlled condition. The temperature and humidity inside and outside the chamber were monitored for one hour. At the initial condition, the outside and inside temperature and humidity are identical as of 22.0 ℃ and 60%, respectively. However, the temperature at the inside chamber during the test dropped from 22.0℃ to 17.0℃, which is 5.0℃ 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 very closely identical to the results of the test. In particular, 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, resulting in dropping the temperature. Water consumption was approximately 4 L during the test. The stabilization of temperature and relative humidity occurred around 50 and 30 minutes later, respectively.

(a)



(b)

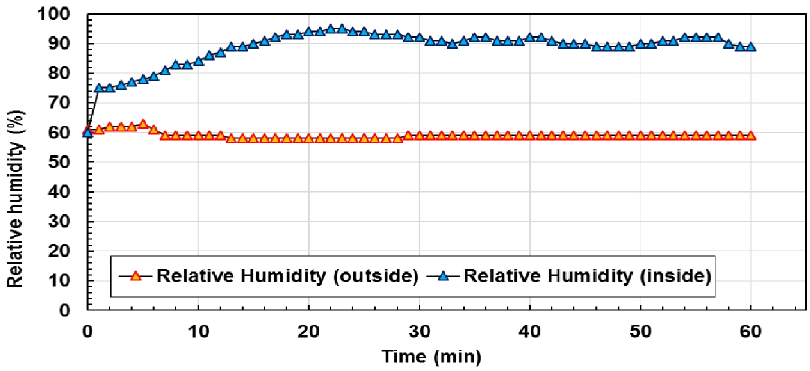


Figure. 5. Variation of temperature and humidity in environmentally controlled condition in laboratory: (a) Temperature and (b) Humidity.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 May 2018 doi:10.20944/preprints201805.0041.v1

3.2. Monitored Temperature and Humidity during the Prototype SFC test

The prototype SFC test was run outside near the campus of NYUAD during two weeks of July and August. The summer in Abu Dhabi is very hot and the outside average temperature reaches to approximate 42.5℃ [24]. Figure. 6 demonstrates the temperature and humidity monitored in the SFC test for the time. The temperature outside ranged from 31.8℃ to 53.9℃. The average and difference in the temperature between the highest and lowest were 37.9 ℃ and 22 ℃, respectively. The temperature inside the compartment ranged from 24.1℃ to 54.4℃. The average and difference of the temperature between the highest and lowest are 31.2℃ and 30.2℃, respectively.

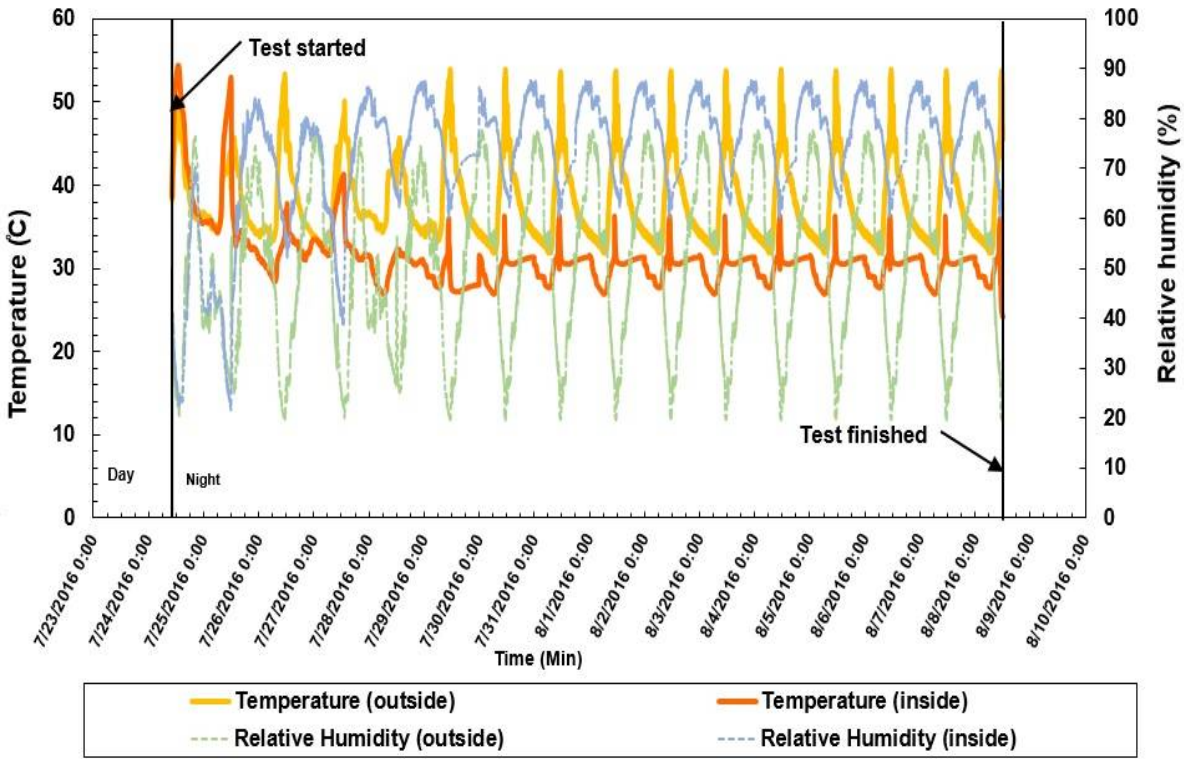


Figure. 6. Variation of temperature and humidity for prototype SFC test for two weeks in July and August.

The outside relative humidity ranged from 19.6% to 77.6%. The average and standard deviation of the relative humidity are 50.7% and 16.2%, respectively. The inside relative humidity ranged from 21.5% to 87.7%. The average and standard deviation of the temperature are 73.2% and 17.4%, respectively. As the relative humidity (inside and outside) 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 the temperature outside and humidity inside was higher than that of the temperature inside and humidity outside. The inside temperature was mostly maintained under 31℃ except the peak times of temperature outside mostly in daytime and specifically around Noon.

Figure. 6 also illustrates that in the first two days the temperature inside and outside the compartment is almost the same. This shows that it takes time for the evaporating coolers to create a shifted new equilibrium inside the system for temperature and humidity. The same trend occurs for relative humidity where after the first two days, it increases over 40% inside the compartment and once again we can see the decreased temperature is related to increasing relative humidity. After day 3, the inside temperature is lowered compared to outside temperature and after day 4 the variation trend of inside temperature is stable for the next 10 days.

Three unexpected peaks of the temperature inside the compartment might be due to high-temperature peaks outside and hence running out of the water to be supplied to the evaporative

 doi:10.20944/preprints201805.0041.v1

cooling system. The water running out can be observed by the sharp drop of the humidity inside the compartment.

3.3. Numerical Simulation

Direct numerical simulations for SFC at Reynolds number of 2300 were performed. The Reynolds number is based on the experimental parameters and prototype SFC geometry. Figure. 7 shows color contours for temperature distribution and arrows for fluid velocity inside the domain as a function of time from unsteady to steady states. Mixing the cool air coming from the evaporate cooling system with inside warm air causes overall temperature drop in the domain. The vertical flow patterns were clearly observed near the top and right end walls, which can also be seen in the temperature contour. These fluid circulations tend to enhance the heat transfer inside the domain.

Figure. 8 shows the time evolution of an area-averaged temperature for the different initial temperatures. The average temperature becomes constant, leading to a thermally steady-state. All different initial temperatures are converged to the same average temperature $T_{ave} \approx 0.19$. It is worth noting that this average temperature corresponds to a temperature drop of approximately 6 - 12℃, depending on the outside temperature. This temperature drop is in good agreement with experimental observations. Thus, the simulation model developed tends to predict the performance of the SFC system very well. The model can be used to explore design and operating issues relevant to the SFC system, which will be included in future work.

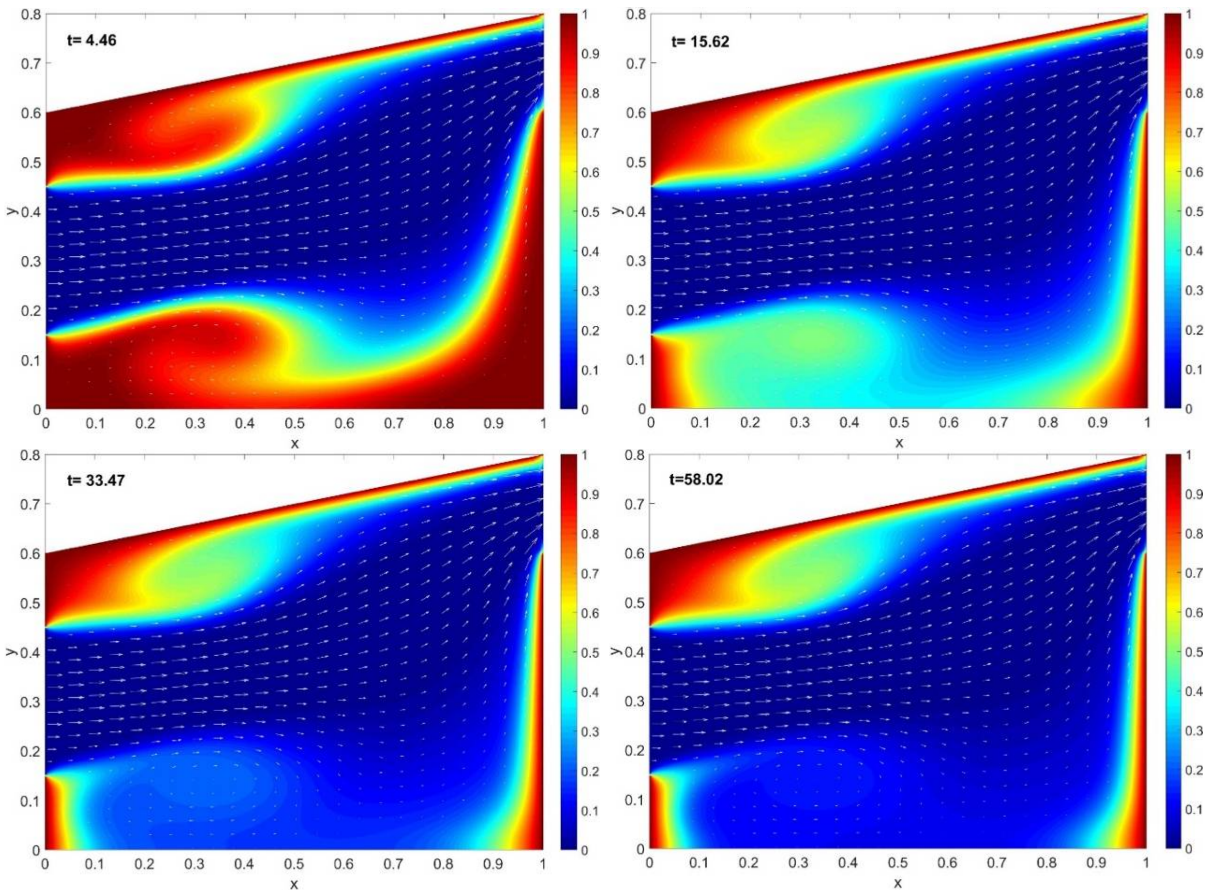


Figure. 7. A contour for temperature distribution and a vector field for fluid flow inside the simulation domain as a function of time at Re = 2300. The case of t = 58.02 can be regarded as a steady state.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 May 2018 doi:10.20944/preprints201805.0041.v1

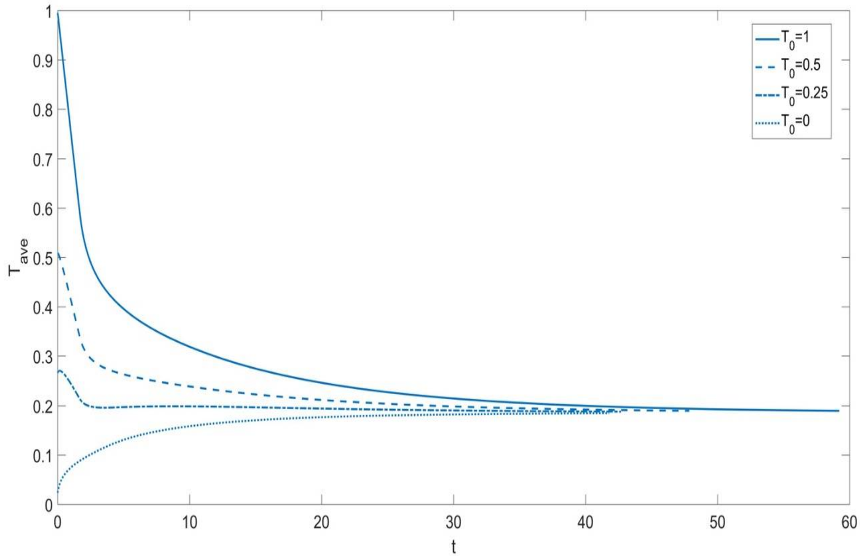


Figure. 8. An area-averaged temperature inside the simulation domain as a function of time at Re = 2300. The four different initial temperatures are used, leading to the same steady-state temperature.

4. Discussion

4.1. Comparison of Data between Experiment and Simulation

Figure. 9 shows the comparison of temperature and humidity obtained from the experimental tests and energy simulation during the testing period. The symbols show the range of the temperature and relative humidity. The boxes show the standard deviation. The average temperature and humidity obtained from the dynamic simulation are 26 ℃ and 78%, respectively. The results show statistically no difference from the paired 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. Thus, the results obtained from the energy simulation shows good agreement with the results from the experimental test.

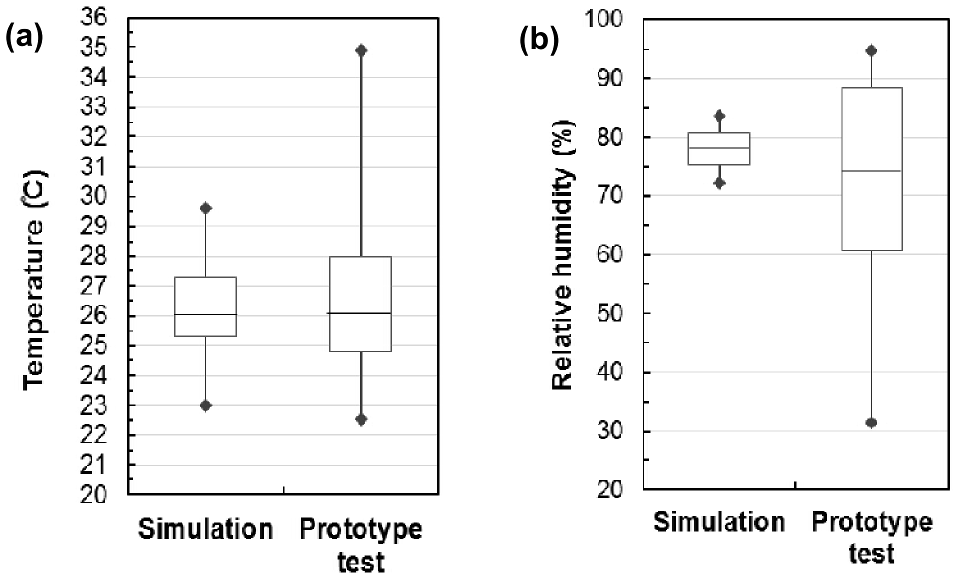


Figure. 9. Comparison of temperature and humidity between dynamic numerical simulation and prototype test: (a) Temperature and (b) Relative humidity.

doi:10.20944/preprints201805.0041.v1

4.2. 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 the compressor. The typical AC requires 5300 W·h for 1.5 tons and 18000 BTU/hour according to the manual of AC [13]. The SFC used in the study is about 0.25 tons. Therefore, the SFC system requires 830 W per one hour by running the AC. However, the SFC system consumed only 260 W per hour, which is almost three and half times lower than that of typical AC system by running evaporative cooling system including five fans and water pump used in this study. Figure. 10 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 the evaporative cooling system is significantly lower than those for AC.

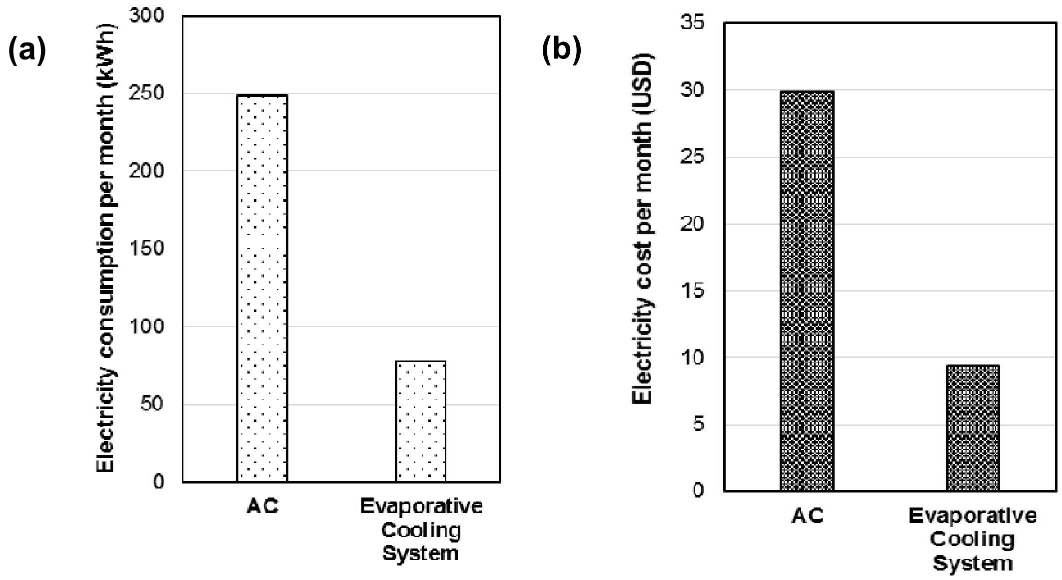


Figure. 10. Comparison of electricity consumption and cost per month (the average cost is 12 cents per watt in the US) between typical AC with compressor and evaporative cooling system to cool down the temperature of the prototype SFC used in the study: (a) Electricity consumption and (b) Electricity cost (USD).

During the test, 132 L of the tap water was consumed per day and per area of the cooling pad. If we assume the treated wastewater used for field compartment system to have approximately eight times larger volume than the prototype SFC in the study, 1060 L water will be consumed per day assuming the environmental condition is identical to the testing condition. Therefore, for the 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.

5. Conclusions

In this study, the concept of the “Oasis” complex comprising of the Sustainable Farming Compartment (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 treated wastewater can be used to decrease the ambient temperature of the SFC via an evaporative cooler. A 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℃ (from average of 38℃) respectively, reaching an average temperature of 31.2℃ (at relative humidity of approximate 50%). Both experimental results coincided with the results from psychrometric chart. The dynamic numerical simulations using a fractional-step method were performed. Simulation results show that with the SFC system there is approximately 6-12℃ temperature drop, which is in good agreement with prototype experimental observations. A dynamic numerical simulation was also performed to extend 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 wastewater 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

Acknowledgments: The authors acknowledge the research department of New York University Abu Dhabi (NYUAD) for funding this study, and Dr. Sam Helwany at NYUAD and Dr. Al-Alili at the Petroleum Institute for their valuable comments.

Author Contributions: Dr. Eun conducted laboratory tests and analyzed the result with Mr. Mousavi. Dr. Park performed numerical simulations and analyzed the results with Mr. Mirfendereski.

References

1. UNCCD, United Nations Convention to Combat Desertification. 1992.
2. Abdelfattah, M. A., Dawoud, M. A. H., & Shahid, S. A. Soil and water management for combating desertification–towards implementation of the United Nations convention to combat desertification from the UAE perspectives. In Proceedings of the International Conference on Soil Degradation, Riga, Latvia, February 2009, pp. 17-19.
3. Abdelfattah, M. A. Land degradation indicators and management options in the desert environment of Abu Dhabi, United Arab Emirates. *Soil Horizons*, **2009**, *50*(1), 3-10. DOI: 10.2136/sh2009.1.0003
4. Abahussain, A. A., Abdu, A. S., Al-Zubari, W. K., El-Deen, N. A., & Abdul-Raheem, M. Desertification in the Arab region: analysis of current status and trends. *Journal of Arid Environments*, **2002**, *51*(4), 521-545. DOI: 10.1016/s0140-1963(02)90975-4
5. Schlesinger, W. H., Reynolds, J. F., Cunningham, G. L., Huenneke, L. F., Jarrell, W. M., Virginia, R. A., & Whitford, W. G. Biological feedbacks in global desertification. *Science (Washington)*, **1990**, *247*(4946), 1043-1048. DOI: 10.1126/science.247.4946.1043
6. Böer, B. An introduction to the climate of the United Arab Emirates. *Journal of Arid Environments*, **1997**, *35*(1), 3-16. DOI: 10.1006/jare.1996.0162
7. EAD, Maximizing recycled water use in the Emirate of Abu Dhabi. 2013. *In Annual Policy Brief*.
8. "The National", UAE, http://www.thenational.ae/uae/environment/plans-to-reuse-100-of-abu-dhabis-waste-water-in-four-years. (Accessed on November 4, 2015)
9. Sahara Forest Project, **2017**, https://www.saharaforestproject.com/wp-content/uploads/2015/03/SFP_-_Intro.pdf.
10. Hatfield, J. L., Prueger, J. H. Temperature extremes: Effect on plant growth and development Weather and Climate Extremes Vol 10, Part A, **2015**, p. 4-10.
11. Camargo, J. R., Ebinuma, C. D., & Silveira, J. L. Experimental performance of a direct evaporative cooler operating during summer in a Brazilian city. *International Journal of Refrigeration*, **2005**, 28 (7), p. 1124–1132. DOI: 10.1016/j.ijrefrig.2004.12.011

12. Wu, J. M., Huang, X., & Zhang, H. Theoretical analysis on heat and mass transfer in a direct evaporative cooler. *Applied Thermal Engineering*, **2009**, *29* (5–6), p. 980–984. DOI: 10.1016/j.applthermaleng.2008.05.016
13. Wu, J. M., Huang, X., & Zhang, H. Numerical investigation on heat and mass transfer in a direct evaporative cooler. *Applied Thermal Engineering*, **2009**, *29* (1), p. 195–201. DOI: 10.1016/j.applthermaleng.2008.02.018
14. Stabat, P, Marchio, D., Orphelin, M. Pre-Design and design tools for evaporative cooling. *ASHRAE Transactions*, **2001**,*107*, p. 501–510.
15. Ibrahim, E., Shao, L., & Riffat, S. B. Performance of porous ceramic evaporators for building the cooling application. *Energy and Buildings*, **2003**, *35*(9), 941-949. DOI: 10.1016/S0378-7788(03)00019-7
16. Lertsatitthanakorn, C., Rerngwongwitaya, S., & Soponronnarit, S. Field experiments and economic evaluation of an evaporative cooling system in a silkworm rearing house. *Biosystems Engineering*, **2006**, *93*(2), 213-219. DOI: 10.1016/j.biosystemseng.2005.12.003
17. Heidarinejad, G., Bozorgmehr, M., Delfani, S., & Esmaeelian, J. Experimental investigation of two-stage indirect/direct evaporative cooling system in various climatic conditions. *Building and Environment*, **2009**, *44*(10), 2073-2079. DOI: 10.1016/j.buildenv.2009.02.017
18. Aljubury, I. M. A., & Ridha, H. D. A. Enhancement of evaporative cooling system in a greenhouse using geothermal energy. *Renewable Energy*, **2017**, *111*, 321-331. DOI: 10.1016/j.renene.2017.03.080
19. Prosperetti, A. & Tryggvason, G. Computational methods for multiphase flow. Cambridge university press: 2009
20. Harlow, F.H. & Welch, J.E. Numerical calculation of time-dependent viscous incompressible flow of fluid with a free surface. *Physics of Fluids*, **1965**, *8*(12), 2182-2189. DOI: 10.1063/1.1761178
21. Ferziger, J.H. & Peric, M. Computational methods for fluid dynamics. Springer Science & Business Media: 2012
22. Kim, J & Moin, P. Application of a fractional-step method to incompressible Navier-Stokes equations, *Journal of Computational Physics*, **1985**, *59*(2), 308-323. DOI: 10.1016/0021-9991(85)90148-2
23. Bell, J.B., Colella, P. & Glaz, H.M. A second-order projection method for the incompressible Navier-Stokes equations. *Journal of Computational Physics*, **1989**, *85*(2), 257-283. DOI: 10.1016/0021-9991(89)90151-4
24. "World Weather Online", https://www.worldweatheronline.com/ (Accessed on December 15, 2017)