CAFEi2016-72

Designing and modeling on-farm desalination system using dew collection technology

O. Mohawesh[1,2,a], K. Unami[2] and M. Fujihara[2]

[1]Faculty of Agriculture, Mutah University, Jordan; [2]Graduate School of Agriculture, Kyoto University, Japan.

Abstract

Water shortage and salinity are crucial factors affecting plant growth in arid and semi-arid regions, where irrigation water shortage and capillary rise from shallow saline water tables are often encountered. The objective of this study is to design a solar-powered greenhouse (GH), and to assess its performance in water production capacity using simulated model. The results showed that the model is capable to predict dew yield and prototype greenhouse (GHp) climate parameters. The GHp performance showed a good agreement between the modeled and the measured dew yield. Overall, the developed model provides a sound basis for describing and explaining the energy and mass balance mechanisms in the developed GHp. The average collected dew was 0.12 l day-1 m-2.These findings would help to predict the potential harvest yield for irrigation. This current work also offers a useful analysis and assessment of the dew yield and energy variations of on-farm desalination using energy and mass balance model. Nevertheless, more general system design and performance analysis based on crop cultivation under a typical arid climate is under evaluation.

Keywords: water scarcity, solar desalination, dew collection, modeling, harsh environment.

INTRODUCTION

Water shortage and salinity are crucial factors affecting plant growth in arid and semi-arid regions, where irrigation water shortage and capillary rise from shallow saline water tables are often encountered (Salameh, 2001). An increasing demand for water, particularly in arid and semi-arid regions, has enforced farmers to use low-quality water sources such as brackish water, saline ground water, and leaching return-flow water for irrigation. Having the knowledge on the level of salinity of such water, it is very important to treat and desalinate this water to retain sustainable agricultural practices (Chaibi, 2000). In light of the addressed water-related problems, novel means to tackle water shortage are essential (Unami et al., 2015).

The scarcity and erratic nature of rainfall make this option a viable solution (Unami et al., 2015). This can be achieved using a technology called humidification-dehumidification greenhouses (Jolliet, 1994; Perret et al., 2005). Water desalination powered by solar energy can help to solve the main problems associated with irrigation water demand, mainly for protected cropping. Desalination process needs considerable quantities of energy to attain separate of salt from saline water. The economic and environmental costs of conventional energy sources for water desalination highlighted the solar energy, as a potential power source for desalination. Renewable-energy systems, which utilizing freely available energy source (solar energy) are sensible sustainable solutions.

Desalination looks appropriate where saline or brackish water is available. The cost of power desalination is not practical methods for arid land farming (Goosen et al., 2001). Several countries are facing water shortage, however, they most benefit from solar energy potential. This desalination method can offer a viable key to supply arid lands with fresh water

[a] E-mail: osam@mutah.edu.jo

(Chaibi, 2000). The approach is to use solar-powered energy through evaporation, to humidify and saturate the air inside the greenhouse using saline water. If its temperature is falling below the dewpoint, which usually happened during the night, condensation of fresh water should potentially occur. This system can be incorporated into the design of the greenhouses in arid regions. Greenlee et al. (2009) stated that desalination is a valuable means of securing water for drinking and agricultural irrigation.

Several studies of solar desalination and its application to greenhouse irrigation have been conducted. Malik et al. (1996) experimentally examined the potential use of greenhouse fitted with solar desalination systems for small-scale farming in areas which only saline or brackish water is available. Chaibi (2002) used simulation model and experiments to explore a greenhouse roof integrated desalination system. He found that the system could be used as a means of supplying irrigation water to greenhouse crops in an arid environment. Medina (2006) indicated that the use of water desalination in agriculture is practical. Zhani (2013) found that a suitable distilled water quality for irrigation was obtained using a theoretical and experimental solar desalination study. Mashaly et al. (2015) found that 1 m^2 of solar-still systems met the crop water requirement of about 2 m^2 of protected cultivation in Saudi Arabia.

A considerable part of the Middle East and North Africa (MENA) region are in such a harsh environment with a precipitation of less than 100 mm $year^{-1}$ (Oroud, 2008; Matouq, 2013). Mohawesh (2016) stated that the agricultural irrigation made up approximately 70% of Jordan's water consumption, where agriculture is the primary job activity and a key role in food security. The Jordan Valley is several degrees warmer than adjacent areas and is compared to function as a giant greenhouse, due to the unique location and all-year good climate conditions (Mohawesh, 2014). The agriculture in Jordan Valley is totally depending on water for irrigation (Molle et al., 2008). However, increased water scarcity, low rainfall, and its uneven distribution, high losses due to evaporation and surface runoff, increased demand due to population growth and deteriorating water qualities are major problems affecting agricultural productivity.

In Jordan Valley, farming is commonly practiced using plastic mulches and trickle irrigation systems. This practice is suitable and effective, either in open fields or under greenhouses due to its advantages in preserving the limited irrigation water resources (Mahadeen et al., 2011; Amayreh and Al-Abed, 2005). The aim of the protected cultivation is not only to provide a suitable environment for crop growth but also it decreases crop water requirements (CWR). The average daily open field crop water requirement in the southern part of the Jordan Valley under mulched and drip irrigation system is 3 mm/day (JVA, 2004). However, protected cultivation requires less water than open-field agriculture, with a reduction in CWR of approximately 20-50% (Harmanto et al., 2005).

The southern part of the Jordan valley, near the south end of the Dead Sea part (Lisan Peninsula (LP)), is characterized by the lowest precipitation, due to its elevation below mean sea level (-420 m below sea level) and high salinity along the coast of the Dead Sea. In LP area, the aridity coupled with over-pumping of ground water has often resulted in water quality deterioration. Irrigating with low water quality has resulted in increasing soil salinity. Accordingly, many cultivated lands in LP are being abandoned or less productive (Ammari et al., 2013). This requires securing freshwater for irrigation, which can be achieved by instigating proper methods for exploiting of saline/brackish water sources. Therefore, the objectives of this study are as follows: design a solar-powerGH , assess its performance in water production capacity using simulated model under numerous scenarios, and to determine the command area that can be met by the solar desalination system.

MATHEMATICAL MODEL FORMULATION

The heat and mass balance of the GH has three major parts: (1) greenhouse cover (GH_{cv}), (2) greenhouse air (GHa), and (3) greenhouse ground surface (GHs). Heat transfer in the GH occurs in three means: conduction /convection, radiation, and latent heat (evaporation) (Figure 1). Models were used to balance mass and heat transfer among these three major parts.

***GH* energy balance**
Greenhouse cover (*GHcv*)

The *GHcv* is a few microns thickness. Hence, the temperatures of the two sides (internal and external) were assumed comparable.

$$dQ_{cv} = Q_{sol,cv} - Q_{cnv,\,cv-a} - Q_{cnv,cv-e} + Q_{cd,cv} - Q_{rad,cv-sky} + Q_{rad,cv} \tag{1}$$

where dQ_{cv} is *GHcv* net energy flux (W m^{-2}), $Q_{sol,cv}$ (W m^{-2}) is solar radiation absorbed by *GHcv*, $Q_{cnv,\,cv-a}$ (W m^{-2}) is convective heat transfer flux between *GHcv* and *GHa*, $Q_{cnv,cv-e}$ (W m^{-2}) is convective heat transfer flux between *GHcv* and greenhouse outside air (*GHe*), $Q_{cd,cv}$ (W m^{-2}) is latent heat produced by water vapour condensation on *GHcv*, $Q_{rad,cv-sky}$ (W m^{-2}) is thermal radiation between *GHcv* and sky, $Q_{rad,cv}$ is thermal radiation balance from the inside and outside of the *GH*.

The $Q_{sol,cv}$ is calculated using the following equation:

$$Q_{sol,cv} = C_{cv,abs} R_s \tag{2}$$

where $C_{cv,abs}$ is *GHcv* solar radiation absorptivity and R_s (W m^{-2}) is solar radiation.

The $Q_{cnv,\,cv-a}$ is calculated using the following equation:

$$Q_{cnv,\,cv-a} = h_{cnv,cv-a}\left(T_{cv} - T_a\right) \tag{3}$$

where $h_{cnv,cv-a}$ (W m^{-2} K^{-1}) is *GHcv* convective heat transfer coefficient between *GHcv* and *GHa*, T_{cv} (K) is *GHcv* temperature, and T_a (K) is *GHa* temperature.

The $Q_{cnv,\,cv-e}$ is calculated by:

$$Q_{cnv,\,cv-e} = h_{cnv,cv-e}\left(T_{cv} - T_e\right) \tag{4}$$

where $h_{cnv,cv-e}$ (W m^{-2} K^{-1}) is *GHcv* convective heat transfer coefficient between *GHcv* and *GHe*, and T_e (K) is *GHe* temperature.

The $Q_{cd,cv}$ is calculated based on *GHcv* temperature as follow:

$$Q_{cd,cv} = h_{cnv,cv-a} L_t \left(H_{cv,sat} - H_{a,a}\right) \tag{5}$$

where L_t (J Kg^{-1}) is latent heat of vaporization, $H_{cv,sat}$ (Kg$_{water}$ Kg$_{air}^{-1}$) is absolute humidity at saturation based on T_{cv}, and $H_{a,a}$ (Kg$_{water}$ Kg$_{air}^{-1}$) is absolute humidity of *GHa*. Condensation takes place when $H_{a,a}$ is greater than $H_{cv,sat}$. The absolute humidity as a function of air vapour pressure (e_a or e_s (Pa)) is calculated using this equation:

$$H = 0.622\left(\frac{e_a}{e_{atm} - e_a}\right) \tag{6}$$

where e_{atm} is atmospheric pressure (Pa), 0.622 is the ratio of molecular weights of water vapour ($18.02 KgKmol^{-1}$) to dry air ($28.97 KgKmol^{-1}$), e_a is actual air vapour pressure, and e_s is saturated vapour pressure. The e_a and e_s (Pa) at temperature T (°C), are calculated by:

$$e_s = 6.1078(7.5T / (T + 237.3))^{10} \quad (7)$$

The $Q_{rad,cv}$ is calculated using this equation:

$$Q_{rad,cv} = Q_{rad,s-cv} + Q_{rad,WRC-cv} + Q_{rad,wditch-cv} = \mu_s \varepsilon_s \sigma T_s^4 + \mu_{WRC} \varepsilon_{WRC} \sigma T_{WRC}^4 + \mu_{wditch} \varepsilon_w \sigma T_{wditch}^4 \quad (8)$$

where μ_{WRC} (-) is WRC area ratio, μ_s (-) is soil surface ratio, μ_{wditch} is water ditch surface ratio, σ (W m^{-2} K^{-4}) is Stefan-Boltzmann constant, T_s, T_{WRC}, and T_{wditch} (K) are GHs, WRC, and water ditch temperatures, respectively.
The $Q_{rad,cv-sky}$ is calculated using the following equation:

$$Q_{rad,cv-sky} = \varepsilon_{cv} \sigma (T_{cv}^4 - T_{sky}^4)(1 - CC) \quad (9)$$

where ε_{cv} (-) is $GHcv$ emissivity, T_{sky} (K) is sky temperature, and CC is fraction of cloud cover.
The T_{sky} is calculated using the following equation:

$$T_{sky}^4 = 9.365574 \times 10^{-6} (1 - CC) T_e^6 + T_e^4 CC \quad (10)$$

GH air (GHa)

$$dQ_a = Q_{cnv,cv-a} + Q_{cnv,s-a} + Q_{cnv,WRC-a} + Q_{cnv,wditch-a} \quad (11)$$

Where dQ_a is GHa net energy flux (W m^{-2}), $Q_{cnv,cv-a}$ (W m^{-2}) is convection heat flux between GHa and $GHcv$, $Q_{cnv,s-a}$ (W m^{-2}) is convection heat flux between GHa and GHs, $Q_{cnv,WRC-a}$ (W m^{-2}) is convection heat flux between GHa and WRC, and $Q_{cnv,wditch-a}$ (W m^{-2}) is convection heat flux between GHa and water ditch.

GH ground surface (GHs)

$$dQ_s = Q_{sol,st} - Q_{cnv,s-a} - Q_{rad-net,s} - Q_{evap,s} \quad (12)$$

where dQ_s is GHs net energy flux (W m^{-2}), $Q_{sol,st}$ (W m^{-2}) is total solar radiation absorbed by GHs, $Q_{cnv,s-a}$ (W m^{-2}) is convection heat flux between GHs and GHa, $Q_{rad-net,s}$ (W m^{-2}) is net thermal radiation flux of GHs, and $Q_{evap,s}$ (W m^{-2}) is the evaporation latent heat flux.
The $Q_{sol,st}$ is calculated using the following equation:

$$Q_{sol,st} = \omega_s C_{abs,s} R_{sol,s} + \omega_w C_{abs,w} R_{sol,s} \quad (13)$$

where ω_s (-) is soil area ratio, $C_{abs,s}$ (-) is GH soil absorbance, $R_{sol,s}$ (W m^{-2}) is solar radiation reach GHs, ω_w (-) is water ditch surface ratio, and $C_{abs,w}$ (-) is water radiation absorbance.

The $Q_{cnv,s-a}$ between GH_s and GH_a is calculated using the following equation:

$$Q_{cnv,s-a} = h_{cnv,s-a}\left(T_s - T_a\right) \tag{14}$$

where $h_{cnv,s-a}$ (W m^{-2} K^{-1}) is the convective heat transfer coefficient between GHs and GHa, and T_s (K) is GHs temperature.

The $Q_{Rad-net,s}$ is calculated using the following equation:

$$Q_{rad-net,s} = Q_{rad,cv-s} + Q_{rad,WRC-s} - Q_{rad,s} = \mu_s \varepsilon_{cv} \sigma T_{cv}^4 + \mu_{WRC} \varepsilon_{WRC} \sigma T_{WRC}^4 - \varepsilon_s \sigma T_s^4 \tag{15}$$

where $Q_{rad,cv-s}$ (W m^{-2}) is thermal radiation between $GHcv$ and GHs, $Q_{rad,WRC-s}$ (W m^{-2}) is thermal radiation between GHs and WRC, $Q_{rad,s}$ (W m^{-2}) is thermal radiation of GHs, μ_s (-) is ((GHs_{area} -WRC_{area}/GHs_{area}) ratio, WRC_{area} (m2) is WRC area, ε_{cv} is $GHcv$ emissivity, μ_{WRC} (-) is (WRC_{area}/GHs_{area}) ratio, ε_{WRC} (-) is WRC emissivity, and T_{WRC} (K) is WRC temperature.

The evaporation energy is calculated from water vapour balance inside GH as follows:

$$Q_{evap,s} = L_t M_{evap,s} \tag{16}$$

where $Q_{evap,s}$ (W m^{-2}) is evaporation thermal energy, and $M_{evap,s}$ (Kg m^{-2}) is mass of evaporative water from GHs.

Water vapour balance

$$dM_a = M_{evap,s} - M_{cd,cv} \tag{17}$$

Where dM_a is vapour net flux (Kg m^{-2}), $M_{evap,s}$ (Kg m^{-2}) is water evaporation from the saline water ditches inside GH, and $M_{cd,cv}$ (Kg m^{-2}) is water vapour condensation flux on $GHcv$.

$$M_{cd,cv} = h_{cnv,cv-a}\left(H_{cv,sat} - H_{a,a}\right) \tag{18}$$

$M_{cd,cv}$ = 0, if $H_{a,a} < H_{cv,sat}$ ($M_{cd,cv}$ takes place when the water vapour concentration of the internal air is greater than the water concentration at saturation calculated based on T_{cv}).

$$M_{evap,s} = h_{cnv,s-a}\left(H_{s,sat} - H_{a,a}\right) \tag{19}$$

where $H_{s,sat}$ ($Kg_{water}\,Kg_{air}^{-1}$) is absolute humidity at saturation based on T_s.

The equation systems (1, 11, 12, and 17) were formulated in a form of a system of ordinary differential equations accompanied with initial and boundary conditions to model and balance mass and heat transfer among the major parts of the GH. Numerical solution based on the fourth-order Runge-Kutta method with adaptive step size control were used to simulate mass and heat transfer in the GH.

PROTOTYPE GH DEW COLLECTION (GH_p)

A GH was established at the water resources engineering experimental station, Kyoto University. The station is located at the coordinates 35° 29\` 23\`\` N, 135° 21\` 57\`\` E on Maizuru Bay, the Sea of Japan. The GH_p is 2.18 m width and 3.58 m length (2.06 m height under the ridge, and 1.19 m height at the roof eaves (gutter)) with a global volume of 12.52 m3 (3.53 m^2 cross-section area). It was oriented with East-West direction. The GH_p was built with a metal frames, covered with polyethylene plastic sheets. The presented GH_p comprises four major parts: $GHcv$, WRC, dew collection measurement instrument, and seawater ditch inside the GH_p. The condensed water vapour adsorbed on the greenhouse roof (GHr) in a drip formation, which either fall or follows the $GHcv$ down to $WRCs$ along GH_p sides, was collected into WRC. Thin plastic sheets were attached to GHr eaves to connect GH_p sides with WRC. The seawater is introduced into the GH_p ditch (0.7 m width, 3.25 m length, and 0.42 m depth) by pumping from the nearby seashore. The WRC (1.18 width, and 1.84 length) was tied to GH side bars using grommet holes at the corners. A small gravel bag was placed at WRC centre discharge point (centre grommet). Then, the collected dew water was drained to a tipping bucket rain gauge (one pulse is equivalent to 4.2764 cm^3 (0.2 mm by 213.82 cm^2)) (HOBO rain gauge RG 165, Onsetcomp, USA). The total tipping numbers and temperature were logged every ten minutes. The GH_p air temperature and relative humidity were measured at two heights: 0.8 m, and near the roof using temperature/relative humidity data loggers (HOBO U23 Pro v2, Onsetcomp, USA). The soil temperature, electrical conductivity, and moisture content were measured using soil moisture and temperature sensors (5TM, Decagon Devices, USA). The outside meteorological data were measured using a meteorological station (HOBO U-30-NRC, Onsetcomp, USA). The measured parameters were logged every ten minutes. The model was verified using three periods: winter (00:00 March 1st until 23:50 March 31, 2015), summer (00:00 June 1st until 23:50 June 31, 2015), and for a long period compiling different weather conditions (00:00 March 1st until 23:50 June 31, 2015 (122 days)). The model results were validated in terms of comparison with the measured collected dew, and measured temperatures inside the GH versus modelled T_{cv}, T_{wditch}, T_{RWC}, and T_a. The average measured collected dew was 0.104 and 0.107 l day^{-1} in March and June, respectively. While, the simulated collected dew was 0.064 (-38.3 %) and 0.148 (+38.1%) l day^{-1} in March and June, respectively. The average measured collected dew was 0.1207 l day^{-1} while the simulated dew was 0.1215 (+<1%) l day^{-1} from 00:00 March 1st until 23:50 June 31, 2015. The good agreement between the simulated and measured data revealed the model competence for comprehending dew amount and modelling GH mass/heat balance.

CONCLUSIONS

The following conclusions can be drawn from the study:

– The results showed that the model is capable to predict dew yield and GH temperatures. The dew yield was sensitive to the meteorological data input. The model underestimated the collected dew yield during March while it is overestimated the modelled dew yield in June.

– The system performance analysis based on longer periods (March 1st to June 31) showed a good agreement between the modelled and the measured dew yield. The average collected dew was 0.12 l day^{-1}. Overall, the developed model provides a sound basis for describing and explaining the energy and mass balance mechanisms in the developed GH.

– Nevertheless, more general system design and performance analysis based on crop cultivation under a typical arid climate is under evaluation.

ACKNOWLEDGEMENTS

Grant-in-aid for scientific research No. 26257415 (JSPS), and Invitation fellowship for research in Japan No. L145461 (JSPS)

Literature cited

Ammari, T.G., Tahhan, R., Abubaker, S., Al-Zu'Bi, Y., and Tahboub, A. (2013). Soil salinity changes in the Jordan Valley potentially threaten sustainable irrigated agriculture. Pedosphere *23*, 376-384.

Chaibi, M.T. (2000). Analysis by simulation of a solar still integrated in a greenhouse roof. Desalination *128,* 123-138.

Chaibi, M.T. (2002). Validation of a simulation model for water desalination in a greenhouse roof through laboratory experiments and conceptual parameter discussions. Desalination *142*, 65-78.

Goosen, M.F.A., Al-Hinai, H., and Sablani, S.S. (2001). Capacity building strategies for desalination: Activities, facilities and educational programs in Oman. Desalination *141*, 181-190.

Greenlee, L.F., Lawler, D.F., Freeman, B.D., Marrot, B., and Moulin, P. (2009). Reverse osmosis desalination: water sources, technology, and today's challenges. Water Res. *43,* 2317-2348.

Harmanto, V.M., Salokhe, M.S., Babel, M.S., and Tantau, H.J. (2005). Water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment. Agr. Water Manage. *71*, 225-242.

Jolliet, O. (1994). Hortitrans, a model for predicting and optimizing humidity and transpiration in greenhouses. J. Agr. Eng. Res. *57,* 23-37.

Malik, M.A.S., Tiwari, G.N., Kumar, A., and Sodha, M.S. (1996). Solar distillation: A practical study of a wide range of stills and their optimum design, construction and performance. Pergamon Press Ltd., Oxford, England, 100-109.

Mashaly, A., Alazba, A., Al-Awaadh, A., and Matter, M. (2015). Area determination of solar desalination system for irrigating crops in greenhouses using different quality feed water. Agr. Water Manage. *154,* 1-10.

Matouq, M., El-Hasan, T., Al-Bilbisi, H., Abdelhadi, M., Hindiyeh, M., Eslamian, S., and Duheisat, S. (2013). The climate change implication on Jordan: A case study using GIS and Artificial Neural Networks for weather forecasting. J. Taibah Uni. Sci. *7(2),* 44-55.

Medina, J.A. (2006). Feasibility of water desalination for agriculture-from water desalination for agricultural applications, Land and Water Discussion Paper, Edited by Beltran JM, Oshima SK, FAO, Rome, *5,* 37-44.

Mohawesh, O. (2016). Utilizing deficit irrigation to enhance growth performance and water use efficiency of eggplant in arid environments. J. Agr. Sci. Tech. *18*, 265-276.

Mohawesh, O. (2014). Development of pedotransfer functions for estimating soil retention curves and saturated hydraulic conductivity in Jordan Valley. Jordan J. Agr. Sci. *10*, 67-82.

Molle, F., Vernot, J.P., and Hassan, Y. (2008). Irrigation in the Jordan Valley: are water pricing policies overly optimistic?. Agr. Water Manage. *95,* 427-438.

Oroud, I. (2008). The impacts of climate change on water resources in Jordan, Climatic changes and water resources in the Middle East and North Africa, Edited by Zereini F, Hötzl H. Environ. Sci. Eng. *9,* 109-123.

Perret, J.S., Al-Ismaili, A.M., and Sablani, S.S. (2005). Development of a humidification-dehumidification system in a Quonset greenhouse for sustainable crop production in arid regions. Biosyst. Eng. 91, 349-359.

Salameh, E. (2001). Sources of water salinities in the Jordan valley area/Jordan. Acta hydrochimica et hydrobiologica *29,* 329-362.

Sharifi, E., Unami, K., Mohawesh, O., Nakamichi, T., Kinjo, N., and Fujihara M (2015) Design and construction of a hydraulic structure for rainwater harvesting in arid environment. Proceedings of the 36th IAHR World Congress, Hague, Netherlands.

Unami, K., Mohawesh, O., Sharifi, E., Takeuchi, J., and Fujihara, M. (2015). Stochastic modelling and control of rainwater harvesting systems for irrigation during dry spells. J. Clean. Prod. *88,* 185-195.

Xing-ming, H., Cong, L., Bin, G., Jian-xin, M., Mubarek, A., Zhong-sheng, C. (2012). Dew formation and its long-term trend in a desert riparian forest ecosystem on the eastern edge of the Taklimakan Desert in China. J. Hydrol. 90–*98,* 472-473.

Zhani, K. (2013). Solar desalination based on multiple effect humidification process: thermal performance and experimental validation. Renew. Sust. Energ. Rev. *24*, 406-417.