UNIVERSITI PUTRA MALAYSIA

PRODUCTIVITY ENHANCEMENT AND MODELLING OF A NEW DOUBLE-SLOPE SOLAR STILL WITH RUBBER SCRAPERS IN LOW LATITUDE AREAS

ALI OMRAN MUHSIN AL-SULTTANI

FK 2018 129

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By

ALI OMRAN MUHSIN AL-SULTTANI

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

February 2018

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DEDICATION

To

The sake of Allah, my Creator and my Master,

My great teacher, the Messenger Mohammed (may Allah bless and grant him),

My mother (Allah save her),

The memory of my father,

My marvellous family,

I dedicate this research

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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By

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February 2018

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Faculty: Engineering

Potable water is vital for our existence. Despite the fact that more than three-quarters of the earth is covered by water, only 0.014% of it is potable. Therefore, sustainable, safe, cheap, and environment-friendly techniques must be developed to produce potable water from salty water. Solar distillation is a promising method that is safe for the environment and uses only sustainable energy for its operation. The productivity of a solar still becomes a major challenge and therefore necessitates many modifications in design and operation to increase its amount. A solar still with high productivity can be achieved when the condensing cover slope is the same as the latitude angle of the solar still location. The main problem that occurs in the solar still is the fall down of water condensate from the glass cover due to gravity.

In this study, a new double slope solar still hybrid with rubber scrapers (DSSSHS) and a double slope solar still (DSSS) were designed with a 3.0° slope condensing cover. The main objective of the study is to obtain the maximum yield of distilled water by using the new DSSSHS during daytime. The proposed design of the new solar still utilizes the advantage of using a condensing cover with a small slope angle to allow the entry of the maximum amount of solar radiation into the still. The disadvantages caused by the condensing cover with a small slope were overcome by using rubber scrapers.

In this research, two (2) double slope solar stills one with rubber scrapers and the other without rubber scrapers were designed and fabricated. In the two solar stills, the condensing cover was placed at 3.0° which is equal to the latitude angle of the experiment location. Several experiments were conducted using the newly designed solar stills under different climatic conditions. The productivities of the two new solar

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stills were measured experimentally. For comparison, the saline water used and the distilled water produced from the DSSSHS were characterized. Experimental results obtained from the DSSSHS were used to construct the prediction models using the linear regression method and particle swarm optimization (PSO) algorithm with the aid of MATLAB software. The prediction models are the regression model, Particle Swarm Optimization Algorithm-Hourly Yield of Solar Still (PSO-HYSS) model, and extended PSO-HYSS model.

In terms of the orientation of the still, there is an increase in daily productivity which varies from 12.3% to 13.2% when using east-west orientation compared with the north-south orientation. Moreover, the experimental results showed that the daily productivity of the DSSSHS (4.24 L/m^2.day) is higher than that of DSSS (2.6 L/m^2.day) under the same design, environmental and operational conditions. This result signifies that the use of rubber scrapers had enhanced the productivity of the still by 63%. The results showed that the productivity of DSSSHS per unit solar radiation is directly proportional to the number of scraper movements per hour (*NSM*). The predicted yields of the three prediction models were compared with their corresponding experimental yields to evaluate their accuracy. The results showed that the extended PSO-HYSS model is the most accurate, followed by the PSO-HYSS model and then the regression model.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENAMBAHBAIKAN PRODUKTIVITI DAN PEMODELAN PENYULING SURIA DWI-CERUN BARU DENGAN PENGIKIS GETAH DI KAWASAN LATITUD RENDAH

Oleh

ALI OMRAN MUHSIN AL-SULTTANI

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Air minum sangat penting untuk kewujudan kita. Walaupun pada hakikatnya lebih daripada tiga suku bumi diliputi air, hanya 0.014% daripadanya boleh diminum. Oleh itu, teknik-teknik yang mampan, selamat, murah, dan mesra alam mesti dibangunkan untuk menghasilkan air minum daripada air masin. Penyulingan suria adalah kaedah yang mempunyai harapan yang selamat bagi alam sekitar dan hanya menggunakan tenaga lestari untuk operasinya. Produktiviti sesuatu penyuling suria menjadi cabaran utama dan oleh itu memerlukan banyak modifikasi dari segi reka bentuk dan operasi untuk meningkatkan jumlahnya. Sebuah penyuling suria berproduktiviti tinggi dapat dicapai apabila cerun penutup pemeluwapan adalah sama dengan sudut latitud lokasi penyuling suria berkenaan. Masalah utama, yang berlaku di penyuling suria , ialah keguguran air peluwap dari penutup kaca disebabkan oleh graviti.

Di dalam kajian ini, satu penyuling suria dwi-cerun baru hibrid dengan pengikis getah (DSSSHS) dan penyuling suria dwi-cerun (DSSS) telah direka dengan penutup pemeluwapan cerun 3.0°. Objektif utama kajian ini adalah untuk mendapatkan hasil maksimum air suling dengan menggunakan DSSSHS baru pada siang hari. Reka bentuk yang dicadangkan untuk penyuling suria baru itu menggunakan kelebihan penggunaan penutup pemeluwapan bersudut cerun kecil untuk membolehkan kemasukan jumlah maksimum sinaran suria ke dalam penyuling. Kelemahan yang disebabkan oleh penutup pemeluwapan dengan cerun kecil telah diatasi dengan menggunakan pengikis getah.

Di dalam penyelidikan ini, dua (2) penyuling suria dwi-cerun dengan dan tanpa pengikis getah telah direka dan dicipta. Di dalam kedua-dua penyuling suria tersebut penutup pemeluwapan diletakkan pada 3.0° yang bersamaan dengan sudut latitud

lokasi eksperimen. Beberapa eksperimen telah dijalankan menggunakan penyuling suria yang baru direka bentuk itu di bawah keadaan cuaca yang berlainan. Produktiviti kedua-dua buah penyuling suria baru itu diukur secara eksperimen. Sebagai perbandingan, air garam yang digunakan dan air suling yang dihasilkan dari DSSSHS dicirikan. Keputusan eksperimen yang diperoleh daripada DSSSHS digunakan untuk membina model-model ramalan menggunakan kaedah regresi linear dan pengoptimuman pengkelompokan zarah (PSO) dengan bantuan perisian MATLAB. Model-model ramalan adalah model regresi, model Algoritma Pengoptimuman Zarah Berkelompok-Hasil Sejam Penyuling Suria (PSO-HYSS), dan model PSO-HYSS yang dilanjutkan.

Daripada segi orientasi penyuling, terdapat peningkatan dalam produktiviti harian yang bervariasi dari 12.3% hingga 13.2% apabila menggunakan orientasi timur-barat berbanding orientasi utara-selatan. Tambahan lagi, keputusan eksperimen menunjukkan bahawa produktiviti harian DSSSHS (4.24 L/m^2.hari) adalah lebih tinggi daripada DSSS (2.6 L/m^2.hari) dengan reka bentuk dan keadaan alam sekitar dan operasi yang sama. Keputusan ini menunjukkan bahawa penggunaan pengikis getah telah meningkatkan produktiviti penyuling sebanyak 63%. Hasil kajian menunjukkan bahawa produktiviti DSSSHS seunit sinaran suria berkadar terus dengan jumlah pergerakan pengikis sejam *(NSM)*. Hasil ramalan dari tiga model ramalan itu dibandingkan dengan hasil eksperimen yang sepadan untuk menilai ketepatannya. Hasil kajian menunjukkan bahawa model PSO-HYSS lanjutan adalah yang paling tepat, diikuti dengan model PSO-HYSS dan kemudiannya model Regresi.

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ACKNOWLEDGEMENTS

بسم الله الرحمن الرحيم

First of all, I wish to express immeasurable gratitude to the One and the Almighty Creator, the Lord of the universe and mankind in particular. Only through His mercy was I able to complete this work.

I also wish to express my gratitude to the Messenger Mohammed (may Allah bless and grant him), who through His pure Biography we learned patience and perseverance to reach our goals.

I would like to express my deepest gratitude to my supervisor Dr. Amimul Ahsan for his invaluable support, guidance, and advice throughout my PhD study. I also wish to express my sincere appreciation to my co-supervisors Dr. Nik Norsyahariati Binti Nik Daud and Dr. Syazwani Binti Idrus for their help and cooperation throughout the study. I also appreciate the assistance of the technical staff of Hydraulics Laboratory, especially Mr. Nik Muhammad Faiz Nik Yahaya; Public Health Laboratory, especially Mr. Aminuddin Amdam; and Structural Engineering Laboratory, especially Mr. Mohammad Haffis Hamid, for their assistance throughout my study.

I am especially grateful to my father, mother, and mother-in-law, who supported me in every way to pursue my study, and to my sisters, whose generosity and kind-heartedness have always been invaluable to me. I also declare my priceless gratitude to my wife Huda for her great sacrifices, understanding, and patience that made this study possible. I also thank my lovely son Zaid and my beautiful daughter Mays for their moral support and encouragement during the entire duration of my study in Malaysia. I would also like to thank all of my friends (Ammar Nasiri, Hussain Adil, Osam Hassan, Ismail Mukhtar, Suhad Dawood, Hassan Farooq, and Ahmed Kadhum) who supported me in sharing ideas and comments and motivating me to strive toward my goal. I would also like to express my gratitude and appreciation to my friends and relatives in Iraq, who did not hesitate to support me during my studies, especially Nadia Naji, Aseel Sady, Saja Laith, Dr. Ban Adnan, Naseer Mosa, Ghazwan Shindi, Riyad Al-Saaidi, Dr. Haidar Hussain, Dr. Ihsan Al-Qadhi and Ahmed Abdul Kadhum. Finally, I would like to express my gratitude to the support provided by Universiti Putra Malaysia (9460700; GP-IPS/2015/9460700). I also acknowledge the scholarship program from Iraq's Ministry of Higher Education and Scientific Research for their assistance and financial support throughout my study.

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LIST OF ABBREVIATIONS

ACO	Ant colony optimization
AD	Adsorption distillation
ANN	Artificial neural networks
APHA	American Public Health Association
AWWA	American Water Works Association
BOD	Biological oxygen demand
CCC	Compound conical concentrator
CDSSS	Conventional double slope single basin solar still
CFD	Computational fluid dynamics
COD	Chemical oxygen demand
CPC-TSS	Compound parabolic concentrator-tubular solar still
CPL	Cost of distilled water per liter
CrSS	Corrugated solar still
CSS	Conventional solar still
CSSSS	Conventional single slope single basin solar still
DE	Differential evolution
DSSS	Double slope solar still
DSSSHS	Double slope solar still hybrid with rubber scrapers
EAs	Evolutionary algorithms
E-W	East-West
EC	Electrical conductivity
ETC	Evacuated tube collector
ED	Electro-dialysis
EP	Evolutionary programming
EPA	Environmental Protection Agency
Extended PSO-HYSS	Extended particle swarm optimization algorithm-hourly yield of solar still
FD	Freeze distillation
FPC	Flat plate collector
FW-BVMED-HR	Floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery

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FWPCA	Federal Water Pollution Control Act
GA	Genetic algorithms
HYSS	Hourly yield of solar still
ITSS	Inclined type solar still
LCD	Liquid crystal display
LHTESS	Latent heat thermal energy storage system
LHTES	Latent heat thermal energy storage
MCRT	Monte Carlo ray-tracing
MED	Multiple effect diffusion
MEU	Multiple-effect unit
MPP	Maximum power tracking prediction
MPPT	Maximum power prediction tracking
MSF	Multi-stage flash distillation
MTC	Mass transfer coefficient
NF	Nano-filtration
N-S	North-South
NSM	Number of scraper movements per hour
PCM	Phase change material
PDC	Parabolic dish concentrator
P&O	Perturb-and-observe
PSO	Particle swarm optimization
PSO-HYSS	Particle swarm optimization algorithm-hourly yield of solar still
PTC	Parabolic trough solar collector
PVT	Photovoltaic thermal
PV	Photovoltaic panel
PW	Paraffin wax
RO	Reverse osmosis
SA	Simulated annealing
SPV	Solar photovoltaic
SSSS	Single slope solar still
TDS	Total dissolved solids
TEC	Thermoelectric cooler

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TSS	Tubular solar still
TWU	Tilted wick unit
TW	Tilted wick
UN-DESA	United Nations, Department of Economic and Social Affairs
UNEP	United Nation Environmental Programme
UPM	Universiti Putra Malaysia
UPW	Ultra-pure water
VCD	Vapor compression distillation
VMED	Vertical multiple effect diffusion solar still
VSBSS	V-corrugated absorber single-basin solar still
WDs	Water depths
WEF	Water Environment Federation
WTSS	Wick type solar still

LIST OF SYMBOLS

A_b	Area of basin liner (m^2)
AFC	Annual fixed cost of the still (US$/year)
AMC	Annual maintenance cost of the still (US$/year)
ASC	Annual salvage cost of the still (US$/year)
A_w	Surface area of the water (m^2)
AWP	Annual water productivity (kg/year)
C	Unknown constant for Nusselt number expression (dimensionless)
C_0	Constant in Equation (4.34)
C_b	Specific heat of basin (J/kg.°C)
$CDWP$	Cost of daily water produced (US$/kg)
C_g	Specific heat of glass cover (J/kg.°C)
CoV	Coefficient of variation (%)
C_v	Specific heat of humid air (J/kg.°C)
C_w	Specific heat of water (J/kg.°C)
c_1; c_2	Cognitive and social acceleration parameters, respectively; "acceleration coefficients"
d	Characteristic length of solar still (m)
D	Number of dimension problems
f	Constant related to the number of movements of the rubber scrapers
fm	Minimum relative improvement of the value of the objective function
g	Gravitational acceleration (9.807 m/s^2)
$gbest$	Global best position of all particles
G_r	Grashof number (dimensionless)
$H_b(t)$	Fraction of absorbed solar radiation by the basin (W/m^2)
$h_{c,b-w}$	Convective heat transfer coefficient from basin liner to water (W/m^2.ºC)
$h_{c,g-a}$	Convective heat transfer coefficient from glass cover to the ambient (W/m^2.°C)
h_{cw}	Convective heat transfer coefficient from water to glass cover (W/m^2.°C)
h_{cwCL}	Convective heat transfer coefficient from water to glass cover for Clark's model (W/m^2.°C)

h_{cwD}	Convective heat transfer coefficient from water to glass cover for Dunkle's model (W/m^2.°C)
h_{cwKT}	Convective heat transfer coefficient from water to glass cover for Kumar and Tiwari's model (W/m^2.°C)
h_{ew}	Evaporative heat transfer coefficient from water to glass cover (W/m^2.°C)
h_{ewD}	Evaporative heat transfer coefficient from water to glass cover for Dunkle's model (W/m^2.°C)
h_{fg}	Latent heat of vaporization (J/kg)
$H_g(t)$	Fraction of absorbed solar radiation by the glass cover (W/m^2)
$h_{r,g\text{-}sky}$	Radiative heat transfer coefficient from glass cover to the sky (W/m^2.°C)
h_{rw}	Radiative heat transfer coefficient from water to glass cover (W/m^2.°C)
h_{rwD}	Radiative heat transfer coefficient from water to glass cover for Dunkle's model (W/m^2.°C)
$H_w(t)$	Fraction of absorbed solar radiation by the water (W/m^2)
h_1	Total internal heat transfer coefficient (W/m^2.°C)
h_{1D}	Total internal heat transfer coefficient for Dunkle's model (W/m^2.°C)
h_{1CL}	Total internal heat transfer coefficient for Clark's model (W/m^2.°C)
h_{1KT}	Total internal heat transfer coefficient for Kumar and Tiwari's model (W/m^2.°C)
K	Thermal conductivity of humid air (W/m.K)
kf	Number of iterations for which the relative improvement of the objective function satisfies the convergence check
k_w	Thermal conductivity of water (W/m.K)
k; k'	Gradient for the regression line between the actual data and the predicted data (dimensionless)
L_w	Characteristic length of water in the basin (m)
m	Constant in Equation (4.34)
MAE	Mean absolute error
$MAPE$	Mean absolute percentage error
m_b	Mass of basin (kg)
M_{Clark}	Hourly predicted yield for Clark's model (kg)
M_{Dunkle}	Hourly predicted yield for Dunkle's model (kg)

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m_{ew}	Hourly theoretical distillate yields (kg)
M_{exp}	Hourly experimental yield (kg)
$M_{extended\ PSO}$	Hourly predicted yield for the extended PSO-HYSS model (L/m^2.h)
m_g	Mass of glass cover (kg)
$M_{Kumar\ and\ Tiwari}$	Hourly predicted yield for Kumar and Tiwari's model (kg)
$MPDW$	Market price of distilled water (US$/kg)
M_{pre}	Hourly predicted yield (kg)
M_{PSO}	Hourly predicted yield for PSO-HYSS model (L/m^2.h)
$M_{Regression}$	Hourly predicted yield for regression model (L/m^2.h)
mp	Performance index (dimensionless)
m_w	Mass of water (kg)
n	Exponent for Nusselt number expression (dimensionless)
N	Number of particles in swarm
NF	Net profit (US$/year)
np	Performance index (dimensionless)
NS	Number of data samples
NSM	Number of scraper movements per hour
Nu	Nusselt number (dimensionless)
$pbest$	Best position for each particle
P_g	Saturation vapor pressure of water at cover temperature (N/m^2)
PI	performance index (dimensionless)
PP	Payback period (day)
Pr	Prandtl number (dimensionless)
P_w	Saturation vapor pressure of water at water temperature (N/m^2)
$q_{b\text{-}a}$	Heat loss from basin liner to the ambient (W/m^2)
$q_{c,b\text{-}w}$	Convective heat transfer rate from basin liner to water (W/m^2)
$q_{c,g\text{-}a}$	Convective heat transfer rate from glass cover to the ambient (W/m^2)
Q_{cw}; q_{cw}	Convective heat transfer rate from water to glass cover (W/m^2)
q_{ew}	Evaporative heat transfer rate from water to glass cover (W/m^2)
q_{ewCL}	Evaporative heat transfer rate from water to glass cover for Clark's model (W/m^2)

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q_{ewKT}	Evaporative heat transfer rate from water to glass cover for Kumar and Tiwari's model (W/m^2)
$q_{r,g\text{-}sky}$	Radiative heat transfer rate from glass cover to the sky (W/m^2)
q_{rw}	Radiative heat transfer rate (W/m^2)
R	Correlation coefficient
$Rand(\cdot)_1$; $Rand(\cdot)_2$	Random variables uniformly distributed within range (*0,1*)
Ra_w	Rayleigh number of water (dimensionless)
ri	Rate of interest taken as 12% of the total fixed cost of the still (%)
R_m	External predictability evaluation index (dimensionless)
RMSE	Root mean square error
RRMSE	Relative root mean square error
R^2	Coefficient of determination
Ro^2	Squared correlation coefficient (through the origin) between predicted and experimental values (dimensionless)
Ro'^2	Squared correlation coefficient (through the origin) between between experimental and predicted values (dimensionless)
S	Constant in Equation (4.31)
Sa	Salvage value of the still (US$)
SATC	Still annual total cost (US$/year)
SR	Solar radiation (W/m^2)
SD	Standard deviation (dimensionless)
T	Maximum number of iterations
t	Number of iterations (generations)
t_{int}	Time interval (s)
T_a	Ambient air temperature (°C)
T_b	Basin temperature (°C)
TFC	Total fixed cost of the still (US$)
T_g	Mean glass covers temperature (°C), (*average of* T_{g1} *and* T_{g2})
T_{g1} , T_{g2}	Glass covers temperatures (°C)
T_v	Vapor temperature; Temperature of humid air inside the still (°C)
T_w	Water temperature (°C)
ul	Useful life of the still (year)

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V_i	Velocity of the particles
w	Inertial weight factor used to balance the global exploration and local exploitation
X_i	Position of the particles
x^L	Lower bound of the number of data samples for the design variables
x^U	Upper bound of the number of data samples for the design variables
y	Actual value
y_{av}	Average actual value
$\acute{y}$	Predicted value
$\acute{y}_{av}$	Average predicted value
z	Constant related to the number of movements of the rubber scrapers

Greek symbols

ε_{eff}	Effective emissivity (dimensionless)
ε_g	Emissivity of glass cover (dimensionless)
ε_w	Emissivity of water (dimensionless)
σ	Stefan-Boltzmann constant (5.6697 x 10^{-8} W/m^2.K^4)
β	Volumetric thermal expansion coefficient (K^{-1})
ΔT	Temperature difference between water and inner side of glass cover (°C)
μ	Dynamic viscosity of humid air (N.s/m^2)
ρv	Mass density of humid air (kg/m^3)
η	Volumetric efficiency (%)
δ_{total}	Total accuracy
δ_{sensor}	Sensor accuracy
$\delta_{instrument}$	Measuring instrument accuracy

Subscripts

a	Ambient
b	Basin
cw	Convective

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ew	Evaporative
g	Glass
rw	Radiative
v	Vapor
w	Water

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CHAPTER 1

INTRODUCTION

1.1 Background

Water resources are abundant on earth, and water covers 71% of the earth's surface; of this value, 97% is sea water, indicating that only 3% of the world's water is fresh and the rest is undrinkable. Out of the 3% fresh water, 2.5% is frozen and locked up in Antarctica, the Arctic, and glaciers, which are rarely available to man. Thus, humanity and the ecosystem must rely on the estimated 0.5% for their fresh water needs (Aves, 2011; Rahimi et al., 2014). Rain is naturally produced through solar desalination and is the main source of fresh water on earth. This natural process is the basis for establishing small-scale man-made distillation systems (Barlow and Reichard, 2010).

Desalination plants are used to convert sea water into drinking water in many arid, coastal, remote, and rugged regions worldwide. Seawater desalination has the potential to produce sufficient potable water to support large populations living near the coast. Numerous membrane filtration seawater desalination plants are in existence. However, this technology is energy intensive; in this regard, scholars have focused on improving its efficiency and reducing its energy consumption (Karuppusamy, 2012). Conventional techniques for water desalination can classified into thermal and membrane types (Khare et al., 2017).

Conventional desalination processes require a significant amount of energy to convert seawater into potable water for human consumption and industrial needs. Several studies were conducted to improve conventional desalination systems. Renewable powered desalination has gained increasing attention due to its economic viability, technological simplicity, and clean energy source.

Solar desalination is another promising method for providing high-quality water to the human community by using a sustainable source. A high demand exists for miniaturization of desalination technologies for treatment of saline water to potable drinking water for consumption in coastal, arid, and remote areas. The development of small scale communal systems for water desalination coupled with solar energy sources has great potential for tackling water supply problems, especially in remote, arid, and coastal areas where sunlight is plentiful. Such systems would also contribute significantly to reduce global warming resulting from CO_2 emissions (Shatat et al., 2013; Winter et al., 2011).

Solar stills use solar radiation to evaporate saline or brackish water. As water evaporates, water vapor rises and condenses on a condensing cover and then streams down the condensing cover into a collector. Solar stills have undergone extensive

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transformations since its introduction in 1950s to improve their productivity (Ang et al., 2017). Several researchers have investigated various types of solar stills, such as weir-type (Sadineni et al., 2008), simple single-basin (Samee et al., 2007), active double-slope (Dwivedi and Tiwari, 2010), tubular (Ahsan, 2009), and portable thermoelectric solar stills (Rahbar and Esfahani, 2012b). Parameters affecting the performance and yield of solar stills have also been investigated (Ahsan et al., 2014a; Feilizadeh et al., 2016; Sathyamurthy et al., 2014a). Moreover, theoretical and numerical approaches have been used to estimate the productivity and heat transfer coefficients of solar stills (Ahsan et al., 2013a; Rahbar and Esfahani, 2012a; Rahbar, N. and J. A. Esfahani, 2013; Rahbar et al., 2015).

The main contributor to low productivity of solar still is the water falling down from the cover of the still toward the basin especially in low latitude areas; this limitation has yet to be addressed. Several researchers have attempted to solve this issue by keeping the inclination angle of the still cover to a minimum of 10° to reduce the amount of falling water as well as the amount of reflected solar radiation (Abdallah et al., 2008; Aybar et al., 2005; Tiwari and Tiwari, 2008). However, this strategy has a negative effect on the productivity of the still because of the decreased amount of solar radiation that enters the still.

To our best knowledge, no study has investigated the use of a mechanical device to prevent the fall down of water condensate from the inner side of the condensing cover toward the basin of the still. Moreover, improving the collection of water condensate and preventing the formation of water film on the inner side of the condensing cover have not been considered. The present study overcome the following major factors that influence the productivity of solar stills: formation of condensate film on the inner side of the cover that reflects a portion of the solar radiation trying to enter the still and re-evaporation of a portion of the water film when exposed to solar radiation.

In this work, two (2) double-slope solar stills one with rubber scrapers and the other without rubber scrapers were designed and fabricated. The condensing cover of the stills was placed at 3.0°, which is equal to the latitude angle of the experiment location. Several experiments were conducted using the newly designed and fabricated solar stills under different climatic conditions. Mathematical models depicting the characteristic thermal behaviors of the newly designed and fabricated solar still systems during the transient operation were studied. Finally, particle swarm optimization (PSO) algorithm was employed to optimize the model parameters in modeling the solar still yield. Figure 1.1(a) and (b) illustrates conventional solar still systems, and Figure 1.1(c) shows the newly designed solar still systems.

New knowledge from this research can be mainly used to enhance the productivity of solar stills and build an accurate hourly yield prediction model especially for solar stills installed in low-latitude areas. The findings of the research will help to alleviate the scarcity of drinking water in coastal, arid, rugged, and remote regions.

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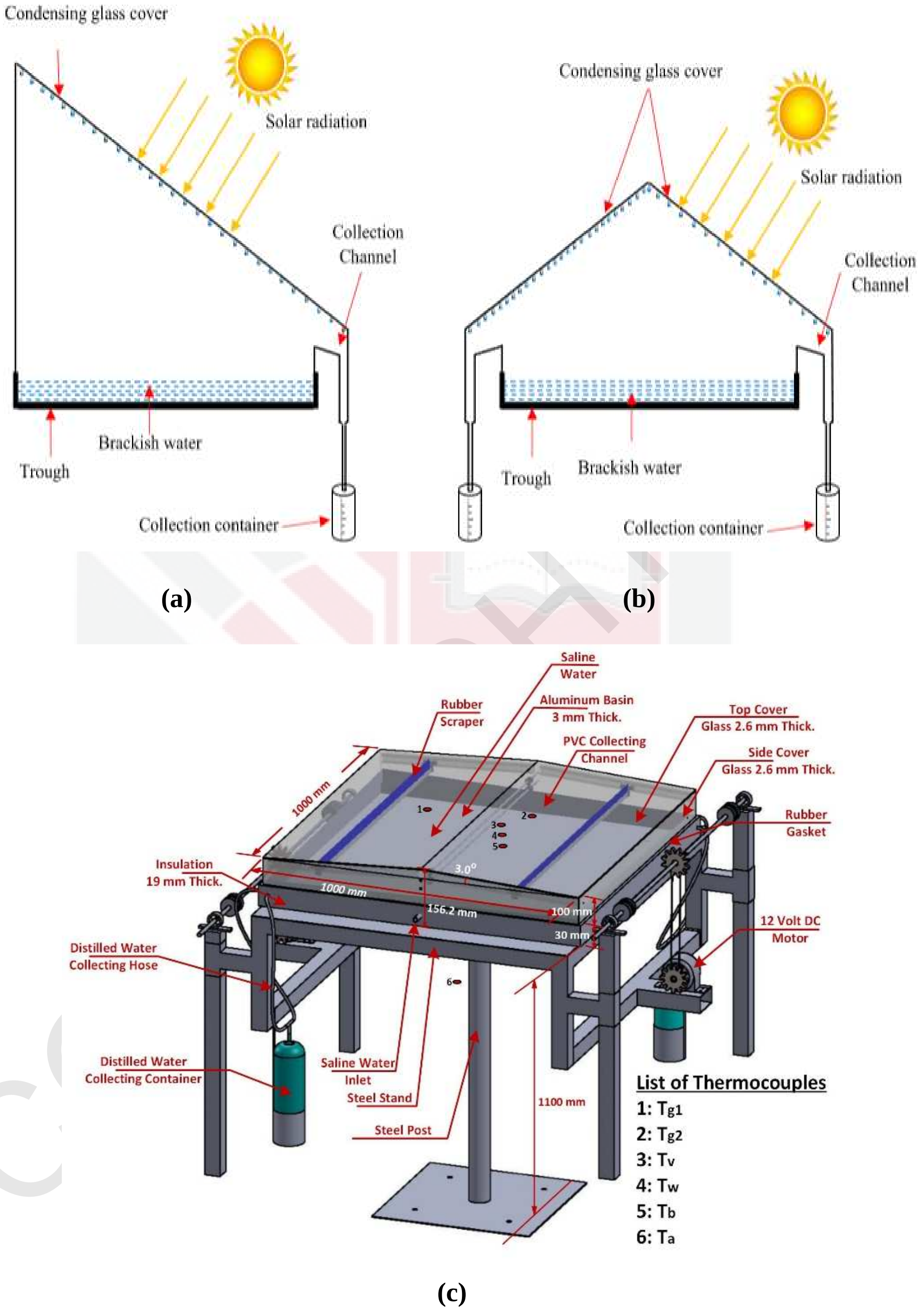

Figure 1.1: Schematic of solar stills: (a) conventional single-slope single-basin solar still, (b) conventional double-slope single-basin solar still, and (c) the proposed design of double-slope solar still hybrid with rubber scrapers (DSSSHS)

1.2 Problem Statements

In the last four decades, alleviating fresh water shortage has become a great challenge worldwide. Despite that more than three-quarters of the earth is covered with water, only 0.014% of it is potable. Sea water constitutes 97.5% of the global water content (UNEP, 2014), as shown in Figure 1.2. In the future, the amount of available fresh water must be increased considering the rise in population and living standards and the expansion of industrial and agricultural activities (Khawaji et al., 2008). According to the new UN-DESA report, “World Population Prospects: The 2015 Revision,” the current world population (7.3 billion) is expected to reach 8.5 billion by 2030, 9.7 billion in 2050, and 11.2 billion in 2100 (UN-DESA, 2015). Therefore, sustainable, safe, cheap, and environment-friendly techniques must be developed to produce potable water from salty water. Solar distillation is an environment-friendly and sustainable technique that can potentially reduce or solve the problem of potable water shortage especially in arid, coastal, remote, and rugged areas (Khawaji et al., 2008). However, the effectiveness of solar distillation technology to treat saline water is still in doubt due to its low productivity which makes the technique not popularly used (Dev and Tiwari, 2011).

The high or low productivity of a solar still depends on many parameters, of which condensing cover angle is one of the most challenging. Many researchers reported that the optimal cover inclination angle is near (Akash et al., 2000; Baibutaev and Achilov, 1968; Baibutaev and Achilov, 1970) or nearly equivalent (Al-Hinai et al., 2002a; Aybar and Assefi, 2009; Elkader, 1998; Khalifa, 2011; Khalifa and Hamood, 2009a; Omri et al., 2005; Samee et al., 2007; Singh and Tiwari, 2004) to the latitude angle of the experiment location. However, Tiwari and Tiwari (2008) reported that the minimum inclination of the glass cover should be at least 10° to avoid falling and/or slowing down the condensate.

In low-latitude areas (wherein the latitude angle is less than 10°), the amount of solar radiation that enters the still increases when the inclination angle for the still cover is close to the latitude angle (Khalifa, 2011). This condition significantly increases the amount of condensed water falling from the inner side of the condensing cover toward the solar still basin, thereby significantly decreasing the productivity of the solar still. Several researchers attempted to solve this problem by keeping the inclination angle of the still cover to a minimum of 10° to reduce the amount of falling water (Abdallah et al., 2008; Aybar et al., 2005; Tiwari and Tiwari, 2008). However, this solution negatively affects the productivity due to the decrease in the amount of solar radiation that enters the solar still. In nutshell, the falling down of water condensate that accumulated on the inner side of the condensing cover toward the basin negatively affects the productivity of solar stills with low-slope cover. Moreover, the presence of condensate film that formed on the inner side of the cover reduces the amount of solar radiation that enters the still, and a portion of the water film re-evaporates upon exposure to solar radiation. Predicting the hourly yield of solar still (HYSS) is another challenge faced by researchers. Dunkle (1961), presented a full mathematical formulation along with a basic theoretical model to predict the mass and heat transfer in solar stills. Although Dunkle’s model is based on many simple assumptions, it has

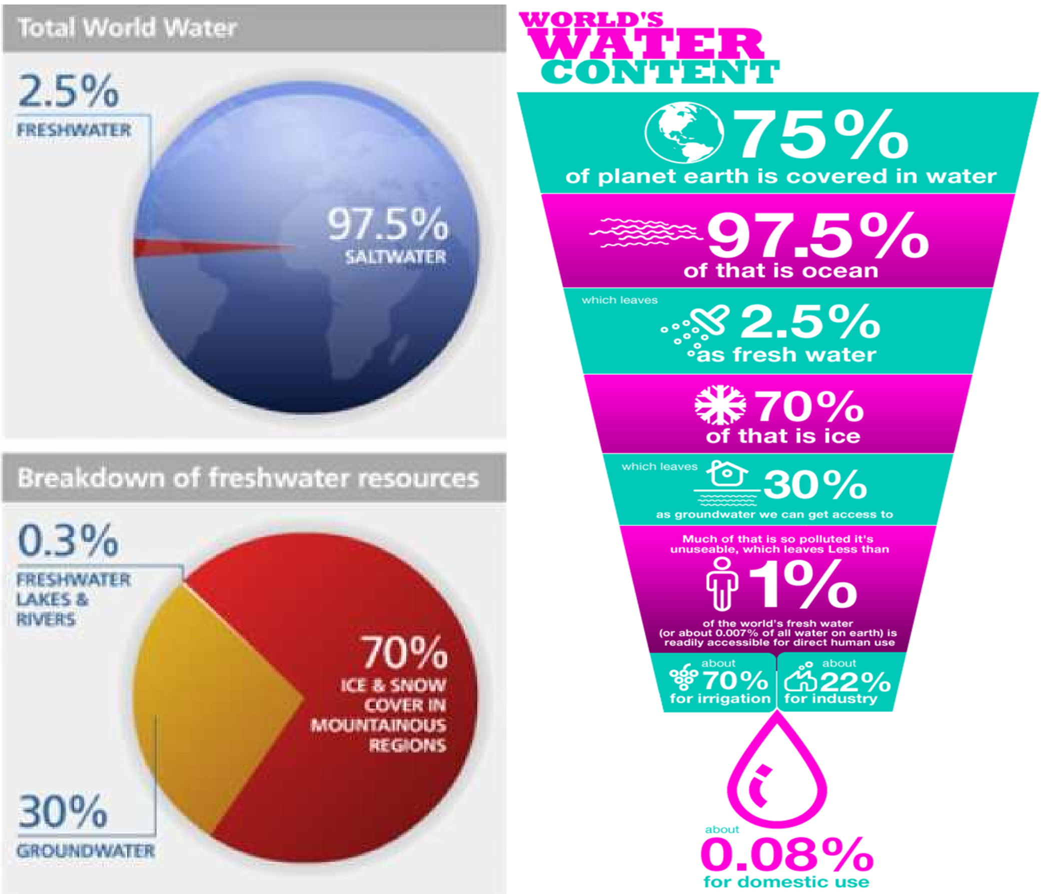

Figure 1.2: World water content (UNEP, 2014)

been extensively used for many years as a simple, accurate, and convenient tool for predicting the yield of solar stills under normal operational conditions. However, the model inaccurately predicts high distillate yield, especially at high average temperatures (Tsilingiris, 2009). After modifying this model and introducing new assumptions and additional limitations, researchers have established several models (Kumar and Tiwari, 1996; Rheinländer, 1982; Tiwari et al., 2003; Tripathi and Tiwari, 2006; Voropoulos et al., 2000). Most of these proposed models inaccurately estimate HYSS as they do not consider the amount of water that falls from the inner surface of the condensing cover of the solar still toward the still basin. This falling water, irrespective of its amount, is inversely proportional to the inclination angle of this condensing cover. Inaccuracy in the experimental HYSS leads to an inaccurate yield prediction model. Moreover, previous yield prediction models, such as Dunkle's model and Kumar and Tiwari's model exhibit low accuracy because they employ conventional trial-and-error procedures to determine different model constants. Furthermore, most researchers did not combine the use of an accurate optimization technique and accurate experimental yields for building HYSS prediction models. They established their models based on conventional trial-and-error methods without considering the amount of condensed water falling from the condensing cover toward the basin of solar still especially in covers with small slopes. All the aforementioned problems can be addressed by the use of rubber scrapers, and an accurate optimization technique i.e., the PSO algorithm to predict the HYSS based on accurate experimental yield values, which was achieved by using the rubber scrapers.

The regression model was developed prior to PSO algorithm to illustrate the importance of considering the amount of water falling from the inner side of the condensing cover toward the basin of the still "which was not considered in the existing models" and its effect on increasing the accuracy of the yield prediction model. The PSO-HYSS model was proposed to develop a yield prediction model that combines between considering the amount of the falling water and the use of PSO algorithm [which has fewer parameters and is easier to implement than a genetic algorithm in addition to showing a faster convergence rate than other evolutionary algorithms for solving some optimization problems (Kennedy et al., 2001)] for the purpose of finding the optimal values of unknown constants to build an accurate yield prediction model, which exceeds the method of trial and error followed in the existing models. This provides more accuracy than the first model. The extended PSO-HYSS model is a model developed from the PSO-HYSS model in order to increase the accuracy of yield prediction and to include the effect of the number of rubber scraper movements per hour *NSM* in the yield prediction model. Figure 1.3 illustrates the schematic of the problem statement.

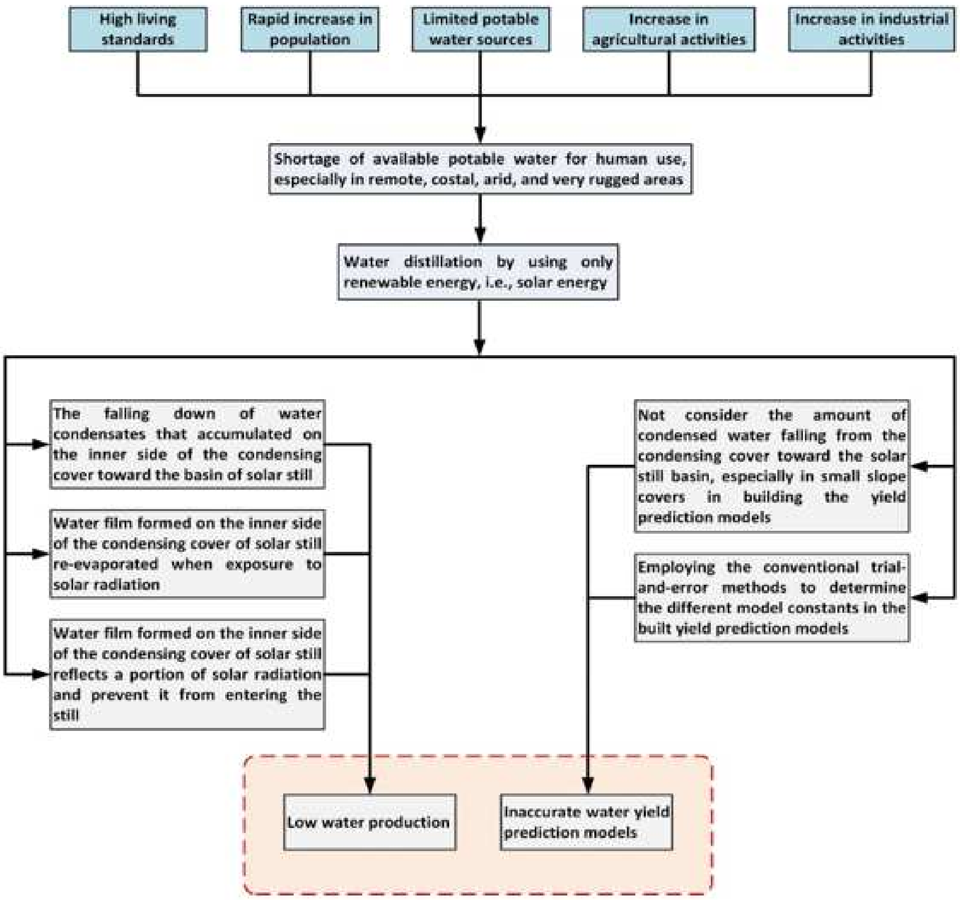

Figure 1.3: Schematic of the problem statement

1.3 Research Objectives

This study aims to improve the productivity of double slope solar still (DSSS) and build an accurate model for predicting the hourly yield of solar still (HYSS). The specific objectives are summarized as follows:

1. To design, fabricate, and perform an experimental investigation on the newly developed double slope solar still hybrid with rubber scrapers (DSSSHS) for seawater treatment and compare its performance with the performance of the double slope solar still (DSSS).

2. To develop a modified regression model for predicting the hourly yield of the DSSSHS using linear regression method.

3. To develop a hybrid particle swarm optimization (PSO) algorithm for developing a statistical yield prediction model which is the particle swarm optimization algorithm-hourly yield of solar still (PSO-HYSS) model for predicting solar still yield (for a wide range of operating temperatures and different environmental and operational parameters).

4. To evaluate the effect of periodic movements of rubber scrapers on the productivity of the DSSSHS and on the accuracy of the yield prediction model. The extended particle swarm optimization algorithm-hourly yield of solar still (extended PSO-HYSS) model was used to represent this effect.

1.4 Significance of the Study

New knowledge from this research can be used to enhance the productivity of solar stills and build an accurate hourly yield prediction model especially for solar stills installed in low-latitude areas. The results will also contribute to elucidate the effects of different parameters, such as water temperature, vapor temperature, glass temperature, water depth, solar radiation, still orientation, and periodic time of rubber scraper movements, on the performance of solar stills. The findings will highlight the importance of using rubber scrapers for collecting condensate in solar stills with a small slope cover and the effects of the scrapers on the productivity of the still. Furthermore, the Nusselt number constants (C and n) and the constants (f and z) related to the number of scraper movements per hour (*NSM*) will be optimized using the PSO algorithm to improve the modeling accuracy. Finally, the findings of the research will help to alleviate the scarcity of drinking water in coastal, arid, rugged, and remote regions.

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1.5 Research Scope and Limitations

The different types of operation and design parameters used in enhancing distillation performance and efficiency are reviewed and discussed. The present work only considered the parameters used to verify the best orientation of solar still and to build yield prediction models. In particular, this study focused on distillation using a solar energy technology to produce potable water from saline water. Few parameters used to build yield prediction models were monitored and discussed. These parameters include ambient temperature, solar radiation, water depth, gap distance, saline water temperature, glass cover temperature, and temperature of the humid air inside the still. Desalination was conducted using a newly developed hybrid solar still. New DSSSHS and DSSS were designed, manufactured, and tested. The proposed DSSSHS utilizes the advantages of using a condensing cover with a small slope in the still (the slope should be equal to the latitude angle of the experiment location) to allow a high amount of solar radiation to enter into the still. The disadvantages caused by the small slope were overcome using rubber scrapers. The effect of shading occurred from the use of rubber scraper is neglected in this study due to its insignificant effect.

Outdoor experiments were carried out at the Faculty of Engineering, University Putra Malaysia, Selangor, Malaysia (latitude N 3° 0′ 27.71″, longitude E 101° 43′ 15.24″ and 45 m height from sea level) between 9:00 to 19:00. Experiments were performed with saline water at different depths (10, 19, and 30 mm). A total of 262 data sets were collected during daytime within 24 days. Data were collected to construct and verify the proposed models. The data sets were classified into the construction and verification groups. Hourly and accumulated total solar radiation, yield, and temperatures were recorded.

In this study, three different models were constructed for predicting the hourly yield of the DSSSHS, based on the experimental yields obtained from the experiments. These models are the regression, PSO-HYSS, and extended PSO-HYSS models. The regression model was developed by using linear regression method to illustrate the importance of considering the amount of water falling from the inner side of the condensing cover toward the basin of the still "which was not considered in the previous existing models" and its effect on increasing the accuracy of the yield prediction model. The other two models which are the PSO-HYSS, and extended PSO-HYSS models were developed using the particle swarm optimization (PSO) algorithm. In the current study, the PSO algorithm was applied for the first time for estimating the optimal values of the unknown set of coefficients for the construction of the PSO-HYSS, and extended PSO-HYSS models for estimating the hourly yield of solar still (HYSS). Three major points were considered before optimizing these models: formulation of all objective functions, use of the PSO algorithm to optimize the model, and use of the convergence criteria.

Three objective functions were used in this study: mean absolute error (MAE), mean absolute percentage error (MAPE), and root mean square error (RMSE). Moreover, the convergence of the current model was determined by terminating the search

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process after identifying the set of coefficients that was able to minimize the objective function. For the current study, two commonly used convergence criteria were selected: the maximal number of iterations of the PSO algorithm and the minimal error required for estimating the optimal values of the objective function. MATLAB software was used to simulate and optimize the PSO-HYSS, and extended PSO-HYSS models for DSSSHS. The PSO-HYSS was proposed for the purpose of developing a yield prediction model combines between considering the amount of the falling water and the use of PSO algorithm for the purpose of finding the optimal values of unknown variables to build the yield prediction model, which exceeds the method of trial and error followed in the previous existing models. This provides more accuracy than the regression model. The extended PSO-HYSS model is a model developed from the PSO-HYSS model in order to increase the accuracy of yield prediction and to include the effect of the number of rubber scraper movements per hour (*NSM*) in the prediction model.

1.6 Thesis Structure

Chapter 1 INTRODUCTION: This chapter presents the study background, problem statements, objectives of the study, significance of the study, scope of the study, and thesis structure.

Chapter 2 LITERATURE REVIEW: This chapter describes the history of desalination systems, types of desalination technologies, overview on solar stills, parameters affecting the productivity of solar still, and comprehensive discussion on different types of desalination enhancement techniques. This section also explains different types of models and thermal enhancement techniques to improve the performance of solar still.

Chapter 3 MATERIALS AND METHODS: This chapter describes the experimental works conduced to achieve the objectives of the study and fill the knowledge gaps identified in literature. This chapter also describes the experimental rig for the DSSSHS and its testing procedure under different environmental conditions. Moreover, this chapter describes the measurement tools employed in this study. The laboratory tests, procedures, and instruments used for testing the quality of saline and distilled water are also described in this chapter.

Chapter 4 THEORETICAL ANALYSIS: This chapter provides details regarding the mathematical equations that describe the performance of the DSSSHS. Mathematical computation is performed using MATLAB software. This chapter also describes the proposed regression model, hybrid PSO–HYSS model, and extended model of PSO–HYSS, which considers the effect of scraper movements. Furthermore, this chapter describes the calculations of error of the yield prediction models with the calculations of the efficiency and cost analysis of the DSSSHS.

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Chapter 5 RESULTS AND DISCUSSION: This chapter presents and discusses the experimental and theoretical results, including the optimum orientation of the DSSS that gives the highest productivity, productivities of the DSSS and DSSSHS, and the theoretical yields obtained from the HYSS prediction models. The modified mathematical models are validated using the experimental results of this study and other existing relevant models in literature.

Chapter 6 CONCLUSIONS AND RECOMMENDATIONS: This chapter concludes the research investigations performed. This chapter highlights the research findings and recommendations for future work.

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REFERENCES

Abdallah, S., and Badran, O. (2008). Sun tracking system for productivity enhancement of solar still. *Desalination, 220*(1-3), 669-676.

Abdallah, S., Badran, O., and Abu-Khader, M. M. (2008). Performance evaluation of a modified design of a single slope solar still. *Desalination, 219*(1-3), 222-230.

Abdel-Rehim, Z. S., and Lasheen, A. (2007). Experimental and theoretical study of a solar desalination system located in Cairo, Egypt. *Desalination, 217*(1), 52-64.

Abdelal, N., and Taamneh, Y. (2017). Enhancement of pyramid solar still productivity using absorber plates made of carbon fiber/CNT-modified epoxy composites. *Desalination, 419*, 117-124.

Abderachid, T., and Abdenacer, K. (2013). Effect of orientation on the performance of a symmetric solar still with a double effect solar still (comparison study). *Desalination, 329*, 68-77.

Abu-Arabi, M., Zurigat, Y., Al-Hinai, H., and Al-Hiddabi, S. (2002). Modeling and performance analysis of a solar desalination unit with double-glass cover cooling. *Desalination, 143*(2), 173-182.

Abujazar, M. S. S., Fatihah, S., Rakmi, A., and Shahrom, M. (2016). The effects of design parameters on productivity performance of a solar still for seawater desalination: A review. *Desalination, 385*, 178-193.

Aggarwal, S., and Tiwari, G. (1998). Convective mass transfer in a double-condensing chamber and a conventional solar still. *Desalination, 115*(2), 181-188.

Ahmed, S. (1988). Study of single-effect solar still with an internal condenser. *Solar & wind technology, 5*(6), 637-643.

Ahsan, A. (2009). *Production model of new tubular solar still and its productivity characteristics*, PhD Thesis, University of Fukui, Japan.

Ahsan, A., and Fukuhara, T. (2008). Evaporative mass transfer in tubular solar still. *Journal of hydroscience and hydraulic engineering, 26*(2), 15-25.

Ahsan, A., and Fukuhara, T. (2010a). Condensation mass transfer in unsaturated humid air inside tubular solar still. *J. Hydrosci. Hydraul. Eng., 28*(1), 31-42.

Ahsan, A., and Fukuhara, T. (2010b). Mass and heat transfer model of tubular solar still. *Solar energy, 84*(7), 1147-1156.

© COPYRIGHT UPM

Ahsan, A., Imteaz, M., Dev, R., and Arafat, H. A. (2013a). Numerical models of solar distillation device: present and previous. *Desalination, 311*, 173-181.

Ahsan, A., Imteaz, M., Rahman, A., Yusuf, B., and Fukuhara, T. (2012). Design, fabrication and performance analysis of an improved solar still. *Desalination, 292*, 105-112.

Ahsan, A., Imteaz, M., Thomas, U., Azmi, M., Rahman, A., and Daud, N. N. (2014a). Parameters affecting the performance of a low cost solar still. *Applied energy, 114*, 924-930.

Ahsan, A., Islam, K. M. S., Fukuhara, T., and Ghazali, A. H. (2010). Experimental study on evaporation, condensation and production of a new tubular solar still. *Desalination, 260*(1), 172-179.

Ahsan, A., Rahman, A., Shanableh, A., Nik Daud, N. N., Mohammed, T. A., and Mabrouk, A. N. (2013b). Life cycle cost analysis of a sustainable solar water distillation technique. *Desalination and water treatment, 51*(40-42), 7412-7419.

Ahsan, A., Syuhada, N., Jolhi, E., Darain, K. M., Rowshon, M. K., Jakariya, M., . . . Ghazali, A. H. (2014b). Assessment of distillate water quality parameters produced by solar still for potable usage. *Fresenius' Environ. Bull., 23*(3a), 859-866.

Akash, B. A., Mohsen, M. S., and Nayfeh, W. (2000). Experimental study of the basin type solar still under local climate conditions. *Energy conversion and management, 41*(9), 883-890.

Akpabio, L. E., and Etuk, S. E. (2003). Relationship between global solar radiation and sunshine duration for Onne, Nigeria. *Turkish Journal of Physics, 27*(2), 161-167.

Al-Hayeka, I., and Badran, O. O. (2004). The effect of using different designs of solar stills on water distillation. *Desalination, 169*(2), 121-127.

Al-Hinai, H., Al-Nassri, M., and Jubran, B. (2002a). Effect of climatic, design and operational parameters on the yield of a simple solar still. *Energy conversion and management, 43*(13), 1639-1650.

Al-Hinai, H., Al-Nassri, M., and Jubran, B. (2002b). Parametric investigation of a double-effect solar still in comparison with a single-effect solar still. *Desalination, 150*(1), 75-83.

© COPYRIGHT UPM

Alaian, W., Elnegiry, E., and Hamed, A. M. (2016). Experimental investigation on the performance of solar still augmented with pin-finned wick. *Desalination, 379*, 10-15.

Ali, H. (1991). Experimental study on air motion effect inside the solar still on still performance. *Energy conversion and management, 32*(1), 67-70.

Ali, H. (1993). Effect of forced convection inside the solar still on heat and mass transfer coefficients. *Energy conversion and management, 34*(1), 73-79.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO, Rome, 300*(9), D05109.

AlRashidi, M., and El-Naggar, K. (2010). Long term electric load forecasting based on particle swarm optimization. *Applied energy, 87*(1), 320-326.

Anburaj, P., Hansen, R. S., and Murugavel, K. K. (2013). Performance of an inclined solar still with rectangular grooves and ridges. *Applied Solar Energy, 49*(1), 22-26.

Ang, W., Nordin, D., Mohammad, A., Benamor, A., and Hilal, N. (2017). Effect of membrane performance including fouling on cost optimization in brackish water desalination process. *Chemical Engineering Research and Design, 117*, 401-413.

Ansari, O., Asbik, M., Bah, A., Arbaoui, A., and Khmou, A. (2013). Desalination of the brackish water using a passive solar still with a heat energy storage system. *Desalination, 324*, 10-20.

Arunkumar, T., Jayaprakash, R., Ahsan, A., Denkenberger, D., and Okundamiya, M. (2013). Effect of water and air flow on concentric tubular solar water desalting system. *Applied energy, 103*, 109-115.

Arunkumar, T., Jayaprakash, R., Denkenberger, D., Ahsan, A., Okundamiya, M., Tanaka, H., and Aybar, H. (2012). An experimental study on a hemispherical solar still. *Desalination, 286*, 342-348.

Arunkumar, T., Velraj, R., Ahsan, A., Khalifa, A., Shams, S., Denkenberger, D., and Sathyamurthy, R. (2016a). Effect of parabolic solar energy collectors for water distillation. *Desalination and water treatment, 57*(45), 21234-21242.

Arunkumar, T., Velraj, R., Denkenberger, D., Sathyamurthy, R., Vinothkumar, K., Porkumaran, K., and Ahsan, A. (2016b). Effect of heat removal on tubular solar desalting system. *Desalination, 379*, 24-33.

© COPYRIGHT UPM

Arunkumar, T., Velraj, R., Denkenberger, D. C., Sathyamurthy, R., Kumar, K. V., and Ahsan, A. (2016c). Productivity enhancements of compound parabolic concentrator tubular solar stills. *Renewable energy, 88*, 391-400.

Asadi, R. Z., Suja, F., and Ruslan, M. H. (2013). The application of a solar still in domestic and industrial wastewater treatment. *Solar energy, 93*, 63-71.

Aves, M. (2011). *Experimental enhancement of single slope solar still,* PhD Thesis, King Fahd University of Petroleum and Minerals (Saudi Arabia).

Aybar, H. Ş., and Assefi, H. (2009). Simulation of a solar still to investigate water depth and glass angle. *Desalination and water treatment, 7*(1-3), 35-40.

Aybar, H. Ş., Egelioğlu, F., and Atikol, U. (2005). An experimental study on an inclined solar water distillation system. *Desalination, 180*(1-3), 285-289.

Badran, O., and Al-Tahaineh, H. (2005). The effect of coupling a flat-plate collector on the solar still productivity. *Desalination, 183*(1-3), 137-142.

Badran, O. O. (2007). Experimental study of the enhancement parameters on a single slope solar still productivity. *Desalination, 209*(1-3), 136-143.

Badran, O. O., and Abu-Khader, M. M. (2007). Evaluating thermal performance of a single slope solar still. *Heat and mass transfer, 43*(10), 985-995.

Bagheri, M., Bagheri, M., Gandomi, A. H., and Golbraikh, A. (2012). Simple yet accurate prediction method for sublimation enthalpies of organic contaminants using their molecular structure. *Thermochimica acta, 543*, 96-106.

Baibutaev, K., and Achilov, B. (1968). Comparative testing of a solar distiller. *Appl. Solar Energy (USSR)(Engl. Transl.);(United States), 4*(5).

Baibutaev, K., and Achilov, B. (1970). Effect of the inclination of the transparent solar-still surface on the condensation and collection processes. *Appl. Solar Energy (USSR)(Engl. Transl.);(United States), 6*(3).

Barlow, P. M., and Reichard, E. G. (2010). Saltwater intrusion in coastal regions of North America. *Hydrogeology Journal, 18*(1), 247-260.

Bland, J. M., and Altman, D. G. (2007). Agreement between methods of measurement with multiple observations per individual. *Journal of biopharmaceutical statistics, 17*(4), 571-582.

© COPYRIGHT UPM

Boqiang, R., and Chuanwen, J. (2009). A review on the economic dispatch and risk management considering wind power in the power market. *Renewable and Sustainable Energy Reviews*, *13*(8), 2169-2174.

Boukar, M., and Harmim, A. (2001). Effect of climatic conditions on the performance of a simple basin solar still: a comparative study. *Desalination*, *137*(1-3), 15-22.

Cheng, Z.-D., He, Y.-L., Du, B.-C., Wang, K., and Liang, Q. (2015). Geometric optimization on optical performance of parabolic trough solar collector systems using particle swarm optimization algorithm. *Applied energy, 148*, 282-293.

Clark, J. A. (1990). The steady-state performance of a solar still. *Solar energy, 44*(1), 43-49.

Coelho, J., de Moura Oliveira, P., and Cunha, J. B. (2005). Greenhouse air temperature predictive control using the particle swarm optimisation algorithm. *Computers and Electronics in Agriculture*, *49*(3), 330-344.

Connor, R. (2015). *The United Nations world water development report 2015: water for a sustainable world* (Vol. 1): UNESCO Publishing.

Cooper, J. (2008). Release on the IAPWS Formulation 2008 for the Thermodynamic Properties of Seawater. *The International Association for the Properties of Water and Steam, September*, 1-19.

Cooper, P. (1983). *Solar distillation: state of the art and future prospects*. Paper presented at the Arab international solar energy conference, 1.

Del Valle, Y., Venayagamoorthy, G. K., Mohagheghi, S., Hernandez, J.-C., and Harley, R. G. (2008). Particle swarm optimization: basic concepts, variants and applications in power systems. *IEEE Transactions on evolutionary computation, 12*(2), 171-195.

Dev, R., and Tiwari, G. (2011). Characteristic equation of the inverted absorber solar still. *Desalination*, *269*(1), 67-77.

Doğan, E., and Saka, M. P. (2012). Optimum design of unbraced steel frames to LRFD–AISC using particle swarm optimization. *Advances in Engineering Software*, *46*(1), 27-34.

Donchyts, G., Baart, F., Winsemius, H., Gorelick, N., Kwadijk, J., and van de Giesen, N. (2016). Earth's surface water change over the past 30 years. *Nature Climate Change*, *6*, 810-813.

© COPYRIGHT UPM

Dorigo, M., Maniezzo, V., and Colorni, A. (1991). Positive feedback as a search strategy. Dipartimento di Elettronica, Politecnico di Milano: Italy, Tech. Rep. 91-016.

Duffle, J., and Beckman, W. (1991). *Solar engineering of thermal processes* (2nd ed.). New York: John Wiley & Sons.

Dunkle, R. (1961). *Solar water distillation; the roof type still and a multiple effect diffusion still* Paper presented at the Proceedings of international heat transfer part V, University of Colorado.

Durkaieswaran, P., and Murugavel, K. K. (2015). Various special designs of single basin passive solar still–A review. *Renewable and Sustainable Energy Reviews, 49*, 1048-1060.

Dwivedi, V., and Tiwari, G. (2010). Experimental validation of thermal model of a double slope active solar still under natural circulation mode. *Desalination, 250*(1), 49-55.

Eaton, A., Clesceri, L. S., Rice, E. W., Greenberg, A. E., and Franson, M. (2005). APHA: Standard Methods for the Examination of Water and Wastewater. *Centennial Edition., APHA, AWWA, WEF, Washington, DC*.

Eberhart, R., and Kennedy, J. (1995). *A new optimizer using particle swarm theory.* Paper presented at the Micro Machine and Human Science, 1995. MHS'95., Proceedings of the Sixth International Symposium.

El-Agouz, S. (2014). Experimental investigation of stepped solar still with continuous water circulation. *Energy conversion and management, 86*, 186-193.

El-Agouz, S., El-Samadony, Y., and Kabeel, A. (2015). Performance evaluation of a continuous flow inclined solar still desalination system. *Energy conversion and management, 101*, 606-615.

El-Maghlany, W. M. (2015). An approach to optimization of double slope solar still geometry for maximum collected solar energy. *Alexandria Engineering Journal, 54*(4), 823-828.

El-Sebaii, A. (2004). Effect of wind speed on active and passive solar stills. *Energy conversion and management, 45*(7), 1187-1204.

El-Sebaii, A. (2011). On effect of wind speed on passive solar still performance based on inner/outer surface temperatures of the glass cover. *Energy, 36*(8), 4943-4949.

© COPYRIGHT UPM

Elango, C., Gunasekaran, N., and Sampathkumar, K. (2015). Thermal models of solar still—A comprehensive review. *Renewable and Sustainable Energy Reviews, 47*, 856-911.

Elango, T., and Murugavel, K. K. (2015). The effect of the water depth on the productivity for single and double basin double slope glass solar stills. *Desalination*, *359*, 82-91.

Elfasakhany, A. (2016). Performance assessment and productivity of a simple-type solar still integrated with nanocomposite energy storage system. *Applied energy*, *183*, 399-407.

Elkader, M. A. (1998). An investigation of the parameters involved in simple solar still with inclined yute. *Renewable energy*, *14*(1), 333-338.

Elminshawy, N. A., Siddiqui, F. R., and Addas, M. F. (2016). Development of an active solar humidification-dehumidification (HDH) desalination system integrated with geothermal energy. *Energy conversion and management, 126*, 608-621.

Eltawil, M. A., Zhengming, Z., and Yuan, L. (2009). A review of renewable energy technologies integrated with desalination systems. *Renewable and Sustainable Energy Reviews*, *13*(9), 2245-2262.

Esfahani, J. A., Rahbar, N., and Lavvaf, M. (2011). Utilization of thermoelectric cooling in a portable active solar still—an experimental study on winter days. *Desalination, 269*(1), 198-205.

Estahbanati, M. K., Ahsan, A., Feilizadeh, M., Jafarpur, K., Ashrafmansouri, S.-S., and Feilizadeh, M. (2016). Theoretical and experimental investigation on internal reflectors in a single-slope solar still. *Applied energy*, *165*, 537-547.

Feilizadeh, M., Estahbanati, M. K., Ahsan, A., Jafarpur, K., and Mersaghian, A. (2016). Effects of water and basin depths in single basin solar stills: An experimental and theoretical study. *Energy conversion and management, 122*, 174-181.

Feng, X., and Papeş, M. (2017). Physiological limits in an ecological niche modeling framework: A case study of water temperature and salinity constraints of freshwater bivalves invasive in USA. *Ecological Modelling*, *346*, 48-57.

Fernández, J., and Chargoy, N. (1990). Multi-stage, indirectly heated solar still. *Solar energy*, *44*(4), 215-223.

© COPYRIGHT UPM

Fiorenza, G., Sharma, V., and Braccio, G. (2003). Techno-economic evaluation of a solar powered water desalination plant. *Energy conversion and management, 44*(14), 2217-2240.

Fong, K., Yuen, S., Chow, C. K., and Leung, S. W. (2010). Energy management and design of centralized air-conditioning systems through the non-revisiting strategy for heuristic optimization methods. *Applied energy, 87*(11), 3494-3506.

Frank, I. E., and Todeschini, R. (1994). *The data analysis handbook* (Vol. 14): Elsevier.

Fu, Q., and Tong, N. (2010). *A new PSO algorithm based on adaptive grouping for photovoltaic MPP prediction.* Paper presented at the Intelligent Systems and Applications (ISA), 2010 2nd International Workshop.

Gandomi, A. H., Alavi, A. H., Shadmehri, D. M., and Sahab, M. (2013). An empirical model for shear capacity of RC deep beams using genetic-simulated annealing. *Archives of Civil and Mechanical Engineering, 13*(3), 354-369.

Gandomi, A. H., and Roke, D. A. (2015). Assessment of artificial neural network and genetic programming as predictive tools. *Advances in Engineering Software, 88,* 63-72.

Golbraikh, A., and Tropsha, A. (2002). Beware of q^2 ! *Journal of Molecular Graphics and Modelling, 20*(4), 269-276.

Good, E. (2010). Estimating daily sunshine duration over the UK from geostationary satellite data. *Weather, 65*(12), 324-328.

Gosling, S. N., and Arnell, N. W. (2016). A global assessment of the impact of climate change on water scarcity. *Climatic Change, 134*(3), 371-385.

Goto, K., Taguchi, S., Fukue, Y., Ohta, K., and Watanabe, H. (1977). Spectrophotometric determination of manganese with 1-(2-pyridylazo)-2-naphthol and a non-ionic surfactant. *Talanta, 24*(12), 752-753.

Hakimi, S., and Moghaddas-Tafreshi, S. (2009). Optimal sizing of a stand-alone hybrid power system via particle swarm optimization for Kahnouj area in south-east of Iran. *Renewable energy, 34*(7), 1855-1862.

Hakimi, S., Tafreshi, S. M., and Kashefi, A. (2007). *Unit sizing of a stand-alone hybrid power system using particle swarm optimization (PSO).* Paper presented at the Automation and logistics, 2007 IEEE international conference.

© COPYRIGHT UPM

Hanoon, A. N., Jaafar, M., Hejazi, F., and Abdul Aziz, F. N. (2016). Energy absorption evaluation of reinforced concrete beams under various loading rates based on particle swarm optimization technique. *Engineering Optimization*, 1-19.

Hanoon, A. N., Jaafar, M., Hejazi, F., and Aziz, F. N. A. (2017). Strut-and-tie model for externally bonded CFRP-strengthened reinforced concrete deep beams based on particle swarm optimization algorithm: CFRP debonding and rupture. *Construction and Building Materials, 147*, 428-447.

Hansen, R. S., Narayanan, C. S., and Murugavel, K. K. (2015). Performance analysis on inclined solar still with different new wick materials and wire mesh. *Desalination, 358*, 1-8.

Harris, S. D., Nagarajan, P., Arunkumar, T., Kannan, E., and Sathyamurthy, R. (2016). Enhancing the solar still yield by increasing the surface area of water—A review. *Environmental Progress & Sustainable Energy, 35*(3), 815-822.

Hashim, A. Y., Al-Asadi, J. M., and Taha, W. A. (2009). Experimental investigation of symmetrical double slope single basin solar stills productivity with different Insulation. *Journal of Kufa-Physics, 1*(2).

Hassan, H., and Abo-Elfadl, S. (2017). Effect of the condenser type and the medium of the saline water on the performance of the solar still in hot climate conditions. *Desalination, 417*, 60-68.

Hidalgo, L. A., and Luna, D. P. (2015). Mathematical modeling and numerical simulation of two-phase flow problems at pore scale. *Electronic journal of differential equations*(22), 79-97.

Holland, J. H. (1992). Genetic algorithms. *Scientific american, 267*(1), 66-72.

Ibrahim, A. G., Allam, E. E., and Elshamarka, S. E. (2015). A modified basin type solar still: Experimental performance and economic study. *Energy, 93*, 335-342.

Ishaque, K., and Salam, Z. (2013). A deterministic particle swarm optimization maximum power point tracker for photovoltaic system under partial shading condition. *IEEE transactions on industrial electronics, 60*(8), 3195-3206.

Ismail, Z., and Abd Aziz, N. (2005). *Monitoring groundwater contamination in Malaysia*. Paper presented at the Proc AEESEAP, Kuala Lumpur.

Jamal, W., and Siddiqui, M. A. (2012). Effect of water depth and still orientation on productivity for passive solar distillation. *Int J Eng Res Appl, 2*(2), 1659-1665.

© COPYRIGHT UPM

Jamil, B., and Akhtar, N. (2016). Effect of Gap Between Absorber Plate and Condenser Cover on the Performance of a Solar Still *Energy, Transportation and Global Warming* (pp. 161-173): Springer.

Kabeel, A. (2009). Performance of solar still with a concave wick evaporation surface. *Energy, 34*(10), 1504-1509.

Kabeel, A., Hamed, A., and El-Agouz, S. (2010). Cost analysis of different solar still configurations. *Energy, 35*(7), 2901-2908.

Kabeel, A., Khalil, A., Omara, Z., and Younes, M. (2012). Theoretical and experimental parametric study of modified stepped solar still. *Desalination, 289*, 12-20.

Kabeel, A., Omara, Z., and Essa, F. (2014). Improving the performance of solar still by using nanofluids and providing vacuum. *Energy conversion and management, 86*, 268-274.

Kabeel, A., Omara, Z., and Younes, M. (2015). Techniques used to improve the performance of the stepped solar still—A review. *Renewable and Sustainable Energy Reviews, 46*, 178-188.

Kalidasa, M. K., and Srithar, K. (2011). Performance study on basin type double slope solar still with different wick materials and minimum mass of water. *Renewable energy, 36*(2), 612-620.

Kannan, R., Selvaganesan, C., Vignesh, M., Babu, B. R., Fuentes, M., Vivar, M., . . . Srithar, K. (2014). Solar still with vapor adsorption basin: Performance analysis. *Renewable energy, 62*, 258-264.

Karaboga, D., and Akay, B. (2009). A survey: algorithms simulating bee swarm intelligence. *Artificial intelligence review, 31*(1-4), 61-85.

Karuppusamy, S. (2012). An experimental study on single basin solar still augmented with evacuated tubes. *Thermal Science, 16*(2), 573-581.

Katsigiannis, Y., Georgilakis, P., and Karapidakis, E. (2010). Multiobjective genetic algorithm solution to the optimum economic and environmental performance problem of small autonomous hybrid power systems with renewables. *IET Renewable Power Generation, 4*(5), 404-419.

Kaushal, A. (2010). Solar stills: A review. *Renewable and Sustainable Energy Reviews, 14*(1), 446-453.

© COPYRIGHT UPM

Kaushal, A., Mittal, M., and Gangacharyulu, D. (2017). An experimental study of floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery. *Desalination, 414*, 35-45.

Kaviani, A. K., Riahy, G., and Kouhsari, S. M. (2009). Optimal design of a reliable hydrogen-based stand-alone wind/PV generating system, considering component outages. *Renewable energy, 34*(11), 2380-2390.

Kaviti, A. K., Yadav, A., and Shukla, A. (2016). Inclined solar still designs: A review. *Renewable and Sustainable Energy Reviews, 54*, 429-451.

Kennedy, J. (2011). Particle swarm optimization *Encyclopedia of machine learning* (pp. 760-766): Springer.

Kennedy, J., Eberhart, R., and Shi, Y. (2001). *Swarm Intelligence, Morgan Kaufmann Publishers*.

Khalifa, A. J. N. (2011). On the effect of cover tilt angle of the simple solar still on its productivity in different seasons and latitudes. *Energy conversion and management, 52*(1), 431-436.

Khalifa, A. J. N., and Hamood, A. M. (2009a). Experimental validation and enhancement of some solar still performance correlations. *Desalination and water treatment, 4*(1-3), 311-315.

Khalifa, A. J. N., and Hamood, A. M. (2009b). On the verification of the effect of water depth on the performance of basin type solar stills. *Solar energy, 83*(8), 1312-1321.

Khaoula, H., Ali, B., Rhomdanne, B. S., and Slimane, G. (2009). Effects of SSD and SSDHP on convective heat transfer coefficient and yields. *Desalination, 249*(3), 1259-1264.

Khare, A., and Rangnekar, S. (2013). A review of particle swarm optimization and its applications in solar photovoltaic system. *Applied Soft Computing, 13*(5), 2997-3006.

Khare, V. R., Singh, A. P., Kumar, H., and Khatri, R. (2017). Modelling and Performance Enhancement of Single Slope Solar Still Using CFD. *Energy Procedia, 109*, 447-455.

Khawaji, A. D., Kutubkhanah, I. K., and Wie, J.-M. (2008). Advances in seawater desalination technologies. *Desalination, 221*(1-3), 47-69.

© COPYRIGHT UPM

Kissinger, B. C., Bystriansky, J., Czehryn, N., Enders, E. C., Treberg, J., Reist, J. D., . . . Anderson, W. G. (2017). Environment-phenotype interactions: Influences of brackish-water rearing on lake trout (Salvelinus namaycush) physiology. *Environmental Biology of Fishes*, 1-18.

Kondo, Y., Phimmasone, V., Ono, Y., and Miyatake, M. (2010). *Verification of efficacy of PSO-based MPPT for photovoltaics.* Paper presented at the Electrical Machines and Systems (ICEMS), 2010 International Conference.

Kongnam, C., and Nuchprayoon, S. (2010). A particle swarm optimization for wind energy control problem. *Renewable energy, 35*(11), 2431-2438.

Kornelakis, A., and Marinakis, Y. (2010). Contribution for optimal sizing of grid-connected PV-systems using PSO. *Renewable energy, 35*(6), 1333-1341.

Kulkarni, R. V., and Venayagamoorthy, G. K. (2011). Particle swarm optimization in wireless-sensor networks: A brief survey. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), 41*(2), 262-267.

Kumar, K. V., and Bai, R. K. (2008). Performance study on solar still with enhanced condensation. *Desalination, 230*(1-3), 51-61.

Kumar, S., and Dwivedi, V. (2015). Experimental study on modified single slope single basin active solar still. *Desalination, 367*, 69-75.

Kumar, S., and Tiwari, G. (1996). Estimation of convective mass transfer in solar distillation systems. *Solar energy, 57*(6), 459-464.

Kumar, S., and Tiwari, G. (2009). Life cycle cost analysis of single slope hybrid (PV/T) active solar still. *Applied energy, 86*(10), 1995-2004.

Lavanya, D., and Udgata, S. K. (2011). *Swarm intelligence based localization in wireless sensor networks.* Paper presented at the International Workshop on Multi-disciplinary Trends in Artificial Intelligence.

Lee, T.-Y., and Chen, C.-L. (2009). Wind-photovoltaic capacity coordination for a time-of-use rate industrial user. *IET Renewable Power Generation, 3*(2), 152-167.

Lee, W.-S., and Lin, L.-C. (2009). Optimal chiller loading by particle swarm algorithm for reducing energy consumption. *Applied Thermal Engineering, 29*(8), 1730-1734.

Liu, L.-q., and Wang, Z.-x. (2009). The development and application practice of wind–solar energy hybrid generation systems in China. *Renewable and Sustainable Energy Reviews, 13*(6), 1504-1512.

© COPYRIGHT UPM

Mahor, A., Prasad, V., and Rangnekar, S. (2009). Economic dispatch using particle swarm optimization: A review. *Renewable and Sustainable Energy Reviews, 13*(8), 2134-2141.

Malaiyappan, P., and Elumalai, N. (2015). Review on Application of Non Conventional Energy Source: Solar Stills. *Journal of Chemical and Pharmaceutical Sciences www. jchps. com ISSN, 974*, 2115.

Malaiyappan, P., and Elumalai, N. (2016). Productivity enhancement of a single basin and single slope solar still coupled with various basin materials. *Desalination and water treatment, 57*(13), 5700-5714.

Malik, M., and Tran, V. V. (1973). A simplified mathematical model for predicting the nocturnal output of a solar still. *Solar energy, 14*(4), 371-385.

Mamouri, S. J., Derami, H. G., Ghiasi, M., Shafii, M., and Shiee, Z. (2014). Experimental investigation of the effect of using thermosyphon heat pipes and vacuum glass on the performance of solar still. *Energy, 75*, 501-507.

Manokar, A. M., Murugavel, K. K., and Esakkimuthu, G. (2014). Different parameters affecting the rate of evaporation and condensation on passive solar still–A review. *Renewable and Sustainable Energy Reviews, 38*, 309-322.

Matrawy, K., Alosaimy, A., and Mahrous, A.-F. (2015). Modeling and experimental study of a corrugated wick type solar still: comparative study with a simple basin type. *Energy conversion and management, 105*, 1261-1268.

Maxfield, A. C. M., and Fogel, L. (1965). Artificial intelligence through a simulation of evolution. *Biophysics and Cybernetics Systems: Proceedings of the Second Cybernetics Sciences. Spartan Books, Washington DC, EE. UU*.

Mishra, D. R., Tiwari, A. K., and Sodha, M. S. (2016). Mathematical modeling and evaluation of new long single slope still for utilization of hot wastewater. *Applied Thermal Engineering, 108*, 353-357.

MOH. (2010). Drinking Water Quality Standard. 2017, from http://kmam.moh.gov.my/public-user/drinking-water-quality-standard.html

Moh'd A, A.-N. (2015). Modeling of a novel concentrated solar still enhanced with a porous evaporator and an internal condenser. *Solar energy, 114*, 8-16.

Moradi, M. H., and Abedini, M. (2012). A combination of genetic algorithm and particle swarm optimization for optimal DG location and sizing in distribution systems. *International journal of electrical power & energy systems, 34*(1), 66-74.

© COPYRIGHT UPM

Mosleh, H. J., Mamouri, S. J., Shafii, M., and Sima, A. H. (2015). A new desalination system using a combination of heat pipe, evacuated tube and parabolic trough collector. *Energy conversion and management, 99*, 141-150.

Muftah, A. F., Alghoul, M., Fudholi, A., Abdul-Majeed, M., and Sopian, K. (2014). Factors affecting basin type solar still productivity: A detailed review. *Renewable and Sustainable Energy Reviews, 32*, 430-447.

Murugavel, K. K., Sivakumar, S., Ahamed, J. R., Chockalingam, K. K., and Srithar, K. (2010). Single basin double slope solar still with minimum basin depth and energy storing materials. *Applied energy, 87*(2), 514-523.

Nafey, A. S., Abdelkader, M., Abdelmotalip, A., and Mabrouk, A. (2000). Parameters affecting solar still productivity. *Energy conversion and management, 41*(16), 1797-1809.

Nakano, S. (1962). Studies on 2, 2'-biquinoline derivatives. VI. Copper chelates of 4, 4'-substituted 2, 2'-biquinoline derivatives and the determination of copper by 2, 2'-bicinchoninic acid. *Yakugaku zasshi: Journal of the Pharmaceutical Society of Japan, 82*, 486.

Ngan, M. S., and Tan, C. W. (2011). Multiple peaks tracking algorithm using particle swarm optimization incorporated with artificial neural network. *World Academy of Science, Engineering and Technology, 58*, 379-385.

NIEA. (2011). European and National Drinking Water Quality Standards. Northern Ireland Environment Agency.

Odhiambo, G. O. (2016). Water scarcity in the Arabian Peninsula and socio-economic implications. *Applied Water Science*, 1-14.

Omara, Z., Hamed, M. H., and Kabeel, A. (2011). Performance of finned and corrugated absorbers solar stills under Egyptian conditions. *Desalination, 277*(1), 281-287.

Omara, Z., Kabeel, A., Abdullah, A., and Essa, F. (2016). Experimental investigation of corrugated absorber solar still with wick and reflectors. *Desalination, 381*, 111-116.

Omara, Z., Kabeel, A., and Younes, M. (2014). Enhancing the stepped solar still performance using internal and external reflectors. *Energy conversion and management, 78*, 876-881.

Omri, A., Orfi, J., and Nasrallah, S. B. (2005). Natural convection effects in solar stills. *Desalination, 183*(1-3), 173-178.

© COPYRIGHT UPM

Panchal, H. N., Patel, M. I., Patel, B., Goswami, R., and Doshi, M. (2011). A comparative analysis of single slope solar still coupled with flat plate collector and passive solar still. *International Journal of Research and Reviews in Applied Sciences, 7*(2), 111-116.

Panchal, H. N., and Shah, P. K. (2014). Enhancement of distillate output of double basin solar still with vacuum tubes. *Frontiers in Energy, 8*(1), 101.

Patel, P., Solanki, A. S., Soni, U. R., and Patel, A. R. (2014). A Review to Increase the Performance of Solar Still: Make It Multi Layer Absorber. *Int. J. Recent Innov. Trends Comput. Commun., 2*, 173-177.

Pekel, J.-F., Cottam, A., Gorelick, N., and Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature, 540*(7633), 418-422.

Phadatare, M., and Verma, S. (2007). Influence of water depth on internal heat and mass transfer in a plastic solar still. *Desalination, 217*(1-3), 267-275.

Pimentel-Gomes, F. (2000). Course of experimental statistics: USPyESALQ, Piracicaba.

Price, K., Storn, R. M., and Lampinen, J. A. (2006). *Differential evolution: a practical approach to global optimization*: Springer Science & Business Media.

Qiblawey, H. M., and Banat, F. (2008). Solar thermal desalination technologies. *Desalination, 220*(1-3), 633-644.

Rababa'h, H. M. (2003). Experimental study of a solar still with sponge cubes in basin. *Energy conversion and management, 44*(9), 1411-1418.

Rabhi, K., Nciri, R., Nasri, F., Ali, C., and Bacha, H. B. (2017). Experimental performance analysis of a modified single-basin single-slope solar still with pin fins absorber and condenser. *Desalination, 416*, 86-93.

Rahbar, N., and Esfahani, J. (2013). Productivity estimation of a single-slope solar still: Theoretical and numerical analysis. *Energy, 49*, 289-297.

Rahbar, N., and Esfahani, J. A. (2012a). Estimation of convective heat transfer coefficient in a single-slope solar still: a numerical study. *Desalination and water treatment, 50*(1-3), 387-396.

Rahbar, N., and Esfahani, J. A. (2012b). Experimental study of a novel portable solar still by utilizing the heatpipe and thermoelectric module. *Desalination, 284*, 55-61.

© COPYRIGHT UPM

Rahbar, N., and Esfahani, J. A. (2013). Productivity estimation of a single-slope solar still: Theoretical and numerical analysis. *Energy, 49*, 289-297.

Rahbar, N., Esfahani, J. A., and Asadi, A. (2016). An experimental investigation on productivity and performance of a new improved design portable asymmetrical solar still utilizing thermoelectric modules. *Energy conversion and management, 118*, 55-62.

Rahbar, N., Esfahani, J. A., and Fotouhi-Bafghi, E. (2015). Estimation of convective heat transfer coefficient and water-productivity in a tubular solar still–CFD simulation and theoretical analysis. *Solar energy, 113*, 313-323.

Rahimi, B., Christ, A., Regenauer-Lieb, K., and Chua, H. T. (2014). A novel process for low grade heat driven desalination. *Desalination, 351*, 202-212.

Rahmani, A., Boutriaa, A., and Hadef, A. (2015). An experimental approach to improve the basin type solar still using an integrated natural circulation loop. *Energy conversion and management, 93*, 298-308.

Rajaseenivasan, T., Kalidasa Murugavel, K., and Elango, T. (2015). Performance and exergy analysis of a double-basin solar still with different materials in basin. *Desalination and water treatment, 55*(7), 1786-1794.

Rajaseenivasan, T., and Murugavel, K. K. (2013). Theoretical and experimental investigation on double basin double slope solar still. *Desalination, 319*, 25-32.

Rajaseenivasan, T., Tinnokesh, A., Kumar, G. R., and Srithar, K. (2016). Glass basin solar still with integrated preheated water supply–theoretical and experimental investigation. *Desalination, 398*, 214-221.

Rashidi, S., Bovand, M., and Esfahani, J. A. (2016). Optimization of partitioning inside a single slope solar still for performance improvement. *Desalination, 395*, 79-91.

Reddy, R., and Reddy, K. (2009). Upward heat flow analysis in basin type solar still. *Journal of Mining and Metallurgy B: Metallurgy, 45*(1), 121-126.

Rheinländer, J. (1982). Numerical calculation of heat and mass transfer in solar stills. *Solar energy, 28*(2), 173-179.

Roy, P. P., and Roy, K. (2008). On some aspects of variable selection for partial least squares regression models. *Molecular Informatics, 27*(3), 302-313.

© COPYRIGHT UPM

Rubio-Cerda, E., Porta-Gándara, M. A., and Fernandez-Zayas, J. L. (2002). Thermal performance of the condensing covers in a triangular solar still. *Renewable energy, 27*(2), 301-308.

Sadineni, S. B., Hurt, R., Halford, C. K., and Boehm, R. F. (2008). Theory and experimental investigation of a weir-type inclined solar still. *Energy, 33*(1), 71-80.

Sahota, L., and Tiwari, G. (2016). Effect of Al 2 O 3 nanoparticles on the performance of passive double slope solar still. *Solar energy, 130*, 260-272.

Samee, M. A., Mirza, U. K., Majeed, T., and Ahmad, N. (2007). Design and performance of a simple single basin solar still. *Renewable and Sustainable Energy Reviews, 11*(3), 543-549.

Sampathkumar, K., Arjunan, T., Pitchandi, P., and Senthilkumar, P. (2010). Active solar distillation—a detailed review. *Renewable and Sustainable Energy Reviews, 14*(6), 1503-1526.

Samsudin, A. R., Haryono, A., Hamzah, U., and Rafek, A. (2008). Salinity mapping of coastal groundwater aquifers using hydrogeochemical and geophysical methods: a case study from north Kelantan, Malaysia. *Environmental Geology, 55*(8), 1737-1743.

Sathyamurthy, R., El-Agouz, S., and Dharmaraj, V. (2015a). Experimental analysis of a portable solar still with evaporation and condensation chambers. *Desalination, 367*, 180-185.

Sathyamurthy, R., Kennady, H. J., Nagarajan, P., and Ahsan, A. (2014a). Factors affecting the performance of triangular pyramid solar still. *Desalination, 344*, 383-390.

Sathyamurthy, R., Nagarajan, P., El-Agouz, S., Jaiganesh, V., and Khanna, P. S. (2015b). Experimental investigation on a semi-circular trough-absorber solar still with baffles for fresh water production. *Energy conversion and management, 97*, 235-242.

Sathyamurthy, R., Nagarajan, P., Subramani, J., Vijayakumar, D., and Ali, K. M. A. (2014b). Effect of water mass on triangular pyramid solar still using phase change material as storage medium. *Energy Procedia, 61*, 2224-2228.

Sathyamurthy, R., Samuel, D. H., and Nagarajan, P. (2016). Theoretical analysis of inclined solar still with baffle plates for improving the fresh water yield. *Process Safety and Environmental Protection, 101*, 93-107.

© COPYRIGHT UPM

Shalaby, S., El-Bialy, E., and El-Sebaii, A. (2016). An experimental investigation of a v-corrugated absorber single-basin solar still using PCM. *Desalination, 398*, 247-255.

Shamim, M. A., Remesan, R., Han, D.-w., Ejaz, N., and Elahi, A. (2012). An improved technique for global daily sunshine duration estimation using satellite imagery. *Journal of Zhejiang University SCIENCE A, 13*(9), 717-722.

Sharma, N. (2012). Stochastic techniques used for optimization in solar systems: A review. *Renewable and Sustainable Energy Reviews, 16*(3), 1399-1411.

Sharon, H., and Reddy, K. (2015). A review of solar energy driven desalination technologies. *Renewable and Sustainable Energy Reviews, 41*, 1080-1118.

Sharon, H., Reddy, K., Krithika, D., and Philip, L. (2017). Experimental performance investigation of tilted solar still with basin and wick for distillate quality and enviro-economic aspects. *Desalination, 410*, 30-54.

Sharqawy, M. H., Lienhard, J. H., and Zubair, S. M. (2010). Thermophysical properties of seawater: a review of existing correlations and data. *Desalination and water treatment, 16*(1-3), 354-380.

Sharqawy, M. H., and Zubair, S. M. (2011). On exergy calculations of seawater with applications in desalination systems. *International Journal of Thermal Sciences, 50*(2), 187-196.

Sharshir, S., Peng, G., Wu, L., Yang, N., Essa, F., Elsheikh, A., . . . Kabeel, A. (2017). Enhancing the solar still performance using nanofluids and glass cover cooling: experimental study. *Applied Thermal Engineering, 113*, 684-693.

Shatat, M., Omer, S., Gillott, M., and Riffat, S. (2013). Theoretical simulation of small scale psychometric solar water desalination system in semi-arid region. *Applied Thermal Engineering, 59*(1), 232-242.

Shi, Y., and Eberhart, R. (1998). *A modified particle swarm optimizer*. Paper presented at the Evolutionary Computation Proceedings, 1998. IEEE World Congress Computational Intelligence., The 1998 IEEE International Conference.

Singh, A., Tiwari, G., Sharma, P., and Khan, E. (1995). Optimization of orientation for higher yield of solar still for a given location. *Energy conversion and management, 36*(3), 175-181.

Singh, D., and Tiwari, G. (2017). Exergoeconomic, enviroeconomic and productivity analyses of basin type solar stills by incorporating N identical PVT compound

© COPYRIGHT UPM

parabolic concentrator collectors: A comparative study. *Energy conversion and management, 135*, 129-147.

Singh, H., and Tiwari, G. (2004). Monthly performance of passive and active solar stills for different Indian climatic conditions. *Desalination, 168*, 145-150.

Sinhaa, A., and Bajpai, P. (2012). *Swarm intelligence based optimal sizing of solar pv, fuel cell and battery hybrid system.* Paper presented at the Proc. of International Conference on Power and Energy Systems Lecture Notes in Information Technology.

Sivakumar, V., and Ganapathy, S. E. (2016). Experimental studies on quality of desalinated water derived from single slope passive solar still. *Desalination and water treatment, 57*(57), 27458-27468.

Smith, G. (1986). Probability and Statistics in Civil Engineering Collins: London.

Soon, J. J., and Low, K.-S. (2012). *Optimizing photovoltaic model parameters for simulation.* Paper presented at the Industrial Electronics (ISIE), 2012 IEEE International Symposium.

Srithar, K., Rajaseenivasan, T., Karthik, N., Periyannan, M., and Gowtham, M. (2016). Stand alone triple basin solar desalination system with cover cooling and parabolic dish concentrator. *Renewable energy, 90*, 157-165.

Suneja, S., and Tiwari, G. (1999). Effect of water depth on the performance of an inverted absorber double basin solar still. *Energy conversion and management, 40*(17), 1885-1897.

Syuhada, N., Ahsan, A., Thomas, U. A., Imteaz, M., and Ghazali, A. H. (2013). A low cost solar still for pure water production. *J. Food Agric. Environ, 11*(2), 990-994.

Tabrizi, F. F., Dashtban, M., and Moghaddam, H. (2010a). Experimental investigation of a weir-type cascade solar still with built-in latent heat thermal energy storage system. *Desalination, 260*(1), 248-253.

Tabrizi, F. F., Dashtban, M., Moghaddam, H., and Razzaghi, K. (2010b). Effect of water flow rate on internal heat and mass transfer and daily productivity of a weir-type cascade solar still. *Desalination, 260*(1), 239-247.

Tabrizi, F. F., and Sharak, A. Z. (2010). Experimental study of an integrated basin solar still with a sandy heat reservoir. *Desalination, 253*(1), 195-199.

Tanaka, H. (2009). Experimental study of a basin type solar still with internal and external reflectors in winter. *Desalination, 249*(1), 130-134.

© COPYRIGHT UPM

Tanaka, H. (2017). Parametric investigation of a vertical multiple-effect diffusion solar still coupled with a tilted wick still. *Desalination, 408*, 119-126.

Tanaka, H., and Iishi, K. (2017). Experimental study of a vertical single-effect diffusion solar still coupled with a tilted wick still. *Desalination, 402*, 19-24.

Thirugnanasambantham, A., Rajan, J., Ahsan, A., and Kandasamy, V. (2013). Effect of air flow on tubular solar still efficiency. *Iranian Journal of Environmental Health Science and Engineering, 10*(1), 31.

Tiwari, A. K., and Tiwari, G. (2005). Effect of the condensing cover's slope on internal heat and mass transfer in distillation: an indoor simulation. *Desalination, 180*(1-3), 73-88.

Tiwari, A. K., and Tiwari, G. (2006). Effect of water depths on heat and mass transfer in a passive solar still: in summer climatic condition. *Desalination, 195*(1-3), 78-94.

Tiwari, A. K., and Tiwari, G. (2007). Thermal modeling based on solar fraction and experimental study of the annual and seasonal performance of a single slope passive solar still: the effect of water depths. *Desalination, 207*(1-3), 184-204.

Tiwari, G., Kupfermann, A., and Aggarwal, S. (1997). A new design for a double-condensing chamber solar still. *Desalination, 114*(2), 153-164.

Tiwari, G., Mukherjee, K., Ashok, K., and Yadav, Y. (1986). Comparison of various designs of solar stills. *Desalination, 60*(2), 191-202.

Tiwari, G., Shukla, S., and Singh, I. (2003). Computer modeling of passive/active solar stills by using inner glass temperature. *Desalination, 154*(2), 171-185.

Tiwari, G., Sinha, S., Saxena, P., and Kumar, S. (1992). Review of solar distiller in other thermal applications. *International journal of solar energy, 13*(2), 135-144.

Tiwari, G., and Tiwari, A. K. (2008). *Solar distillation practice for water desalination systems*. United Kingdom: Anshan.

Tripathi, R., and Tiwari, G. (2005). Effect of water depth on internal heat and mass transfer for active solar distillation. *Desalination, 173*(2), 187-200.

Tripathi, R., and Tiwari, G. (2006). Thermal modeling of passive and active solar stills for different depths of water by using the concept of solar fraction. *Solar energy, 80*(8), 956-967.

© COPYRIGHT UPM

Tsilingiris, P. (2009). Analysis of the heat and mass transfer processes in solar stills–The validation of a model. *Solar energy, 83*(3), 420-431.

Tudu, B., Majumder, S., Mandal, K. K., and Chakraborty, N. (2011). *Comparative performance study of genetic algorithm and particle swarm optimization applied on off-grid renewable hybrid energy system.* Paper presented at the International Conference on Swarm, Evolutionary, and Memetic Computing.

Ugwuoke, E., Ukwuani, S., Okeke, C., Orban, M., and Okpanachi, A. (2015). Design and Evaluation of a Portable Water Distillation System. *International Journal Advanced Engineering Research and Science*.

UN-DESA. (2015). World Population Prospects: The 2015 Revision: United Nations, Department of Economic and Social Affairs Population Devision. from https://esa.un.org/unpd/wpp/

UNEP. (2014). United Nation Environmental Programme. from www.unep.org/

Velmurugan, V., Deenadayalan, C., Vinod, H., and Srithar, K. (2008a). Desalination of effluent using fin type solar still. *Energy, 33*(11), 1719-1727.

Velmurugan, V., Gopalakrishnan, M., Raghu, R., and Srithar, K. (2008b). Single basin solar still with fin for enhancing productivity. *Energy conversion and management, 49*(10), 2602-2608.

Velmurugan, V., Kumar, K. N., Haq, T. N., and Srithar, K. (2009a). Performance analysis in stepped solar still for effluent desalination. *Energy, 34*(9), 1179-1186.

Velmurugan, V., Pandiarajan, S., Guruparan, P., Subramanian, L. H., Prabaharan, C. D., and Srithar, K. (2009b). Integrated performance of stepped and single basin solar stills with mini solar pond. *Desalination, 249*(3), 902-909.

Velmurugan, V., and Srithar, K. (2011). Performance analysis of solar stills based on various factors affecting the productivity—A review. *Renewable and Sustainable Energy Reviews, 15*(2), 1294-1304.

Villacorte, L. O. (2014). *Algal blooms and membrane based desalination technology*: UNESCO-IHE, Institute for Water Education.

Voropoulos, K., Mathioulakis, E., and Belessiotis, V. (2000). Transport phenomena and dynamic modeling in greenhouse-type solar stills. *Desalination, 129*(3), 273-281.

© COPYRIGHT UPM

Wai, R.-J., Cheng, S., and Chen, Y.-C. (2011). *Installed capacity optimization of hybrid energy generation system.* Paper presented at the Industrial Electronics and Applications (ICIEA), 2011 6th IEEE Conference.

Wang, L., and Singh, C. (2007). *Compromise between cost and reliability in optimum design of an autonomous hybrid power system using mixed-integer PSO algorithm.* Paper presented at the Clean Electrical Power, 2007. ICCEP'07. International Conference.

Ward, J. (2003). A plastic solar water purifier with high output. *Solar energy, 75*(5), 433-437.

Wassouf, P., Peska, T., Singh, R., and Akbarzadeh, A. (2011). Novel and low cost designs of portable solar stills. *Desalination, 276*(1-3), 294-302.

WHO. (2004). *Guidelines for drinking-water quality* (Vol. 1): World Health Organization.

WHO. (2007). Desalination for safe water supply: guidance for the health and environmental aspects applicable to desalination. *World Health Organization, Geneva*.

WHO. (2011). Guidelines for drinking-water quality. *World Health Organization: Geneva, Switzerland*.

Wilf, M., Awerbuch, L., Bartels, C., Mickley, M., Pearce, G., and Voutchkov, N. (2007). The guidebook to membrane desalination technology. *Balaban Desalination Publication, L'Aquila, Italy*.

Winter, D., Koschikowski, J., and Wieghaus, M. (2011). Desalination using membrane distillation: Experimental studies on full scale spiral wound modules. *Journal of Membrane Science, 375*(1), 104-112.

Xie, F., Wang, Q.-j., and Li, G.-l. (2012). *Optimization research of FOC based on PSO of induction motors.* Paper presented at the Electrical Machines and Systems (ICEMS), 2012 15th International Conference.

Xie, G., Sun, L., Mo, Z., Liu, H., and Du, M. (2016). Conceptual design and experimental investigation involving a modular desalination system composed of arrayed tubular solar stills. *Applied energy, 179*, 972-984.

Xiong, J., Xie, G., and Zheng, H. (2013). Experimental and numerical study on a new multi-effect solar still with enhanced condensation surface. *Energy conversion and management, 73*, 176-185.

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Yang, B., Chen, Y., and Zhao, Z. (2007). *Survey on applications of particle swarm optimization in electric power systems.* Paper presented at the Control and Automation, 2007. ICCA 2007. IEEE International Conference on.

Yuen, S. Y., and Chow, C. K. (2009). A genetic algorithm that adaptively mutates and never revisits. *IEEE Transactions on evolutionary computation, 13*(2), 454-472.

Zala, B., Dodia, K., and Panchal, H. N. (2013). Present status of solar still: a critical review. *International Journal of Research Review in Engineering Science and Technology, 2*(1), 6-11.

Zurigat, Y. H., and Abu-Arabi, M. K. (2004). Modelling and performance analysis of a regenerative solar desalination unit. *Applied Thermal Engineering, 24*(7), 1061-1072.

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