



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

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By

ALI OMRAN MUHSIN AL-SULTTANI

**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



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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February 2018

Chairman: Amimul Ahsan, PhD
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

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/m².day) is higher than that of DSSS (2.6 L/m².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

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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 ($4.24 \text{ L/m}^2 \cdot \text{hari}$) adalah lebih tinggi daripada DSSS ($2.6 \text{ L/m}^2 \cdot \text{hari}$) 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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I certify that a Thesis Examination Committee has met on 23 February 2018 to conduct the final examination of Ali Omran Muhsin Al-Sulttani on his thesis entitled "Productivity Enhancement and Modelling of a New Double-Slope Solar Still with Rubber Scrapers in Low Latitude Areas" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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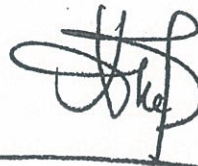
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TABLE OF CONTENTS

	Page
ABSTRACT	i
ABSTRAK	iii
ACKNOWLEDGEMENTS	v
APPROVAL	vi
DECLARATION	viii
LIST OF TABLES	xiv
LIST OF FIGURES	xvi
LIST OF ABBREVIATIONS	xxi
LIST OF SYMBOLS	xxiv
CHAPTER	
1 INTRODUCTION	1
1.1 Background	1
1.2 Problem Statements	4
1.3 Research Objectives	7
1.4 Significance of the Study	7
1.5 Research Scope and Limitation	8
1.6 Thesis Structure	9
2 LITERATURE REVIEW	11
2.1 Introduction	11
2.2 Global Water Resources	11
2.3 Environmental Sustainability of Water Scarce Zones	11
2.4 Sea Water Characterization	12
2.5 History of Desalination	12
2.6 Solar Energy for Desalination Application	13
2.6.1 Desalination Technologies	13
2.6.2 Classification of Solar Desalination Systems	13
2.7 Solar Still System	14
2.7.1 Classification of Solar Stills	15
2.7.1.1 Passive Solar Still	15
2.7.1.2 Active Solar Still	32
2.7.2 Productivity of Solar Still	34
2.7.3 Parameters Affecting the Productivity of Single Basin Double Slope Solar Still	35
2.7.3.1 Environmental Parameters	36
2.7.3.2 Design Parameters	38
2.7.3.3 Operating Parameters	41
2.8 Heat Transfer and Thermal Modeling	43
2.9 Background on Particle Swarm Optimization (PSO) Algorithm	46
2.9.1 General Applications Particle Swarm Optimization (PSO) Algorithm	47

2.9.2	Applications of Particle Swarm Optimization (PSO) Algorithm in Solar Energy Systems	48
2.10	Cost analysis of Solar still	50
2.11	Rubber Scrapers	50
2.12	Product Water Quality	50
2.13	Summary	53
3	MATERIALS AND METHODS	55
3.1	Introduction	55
3.2	Sequence of Investigation	55
3.3	Investigative Tools	57
3.4	Descriptions of the Experimental Test Rig Set-up	57
3.4.1	Solar Still Construction	57
3.4.1.1	Trough	58
3.4.1.2	Condensing Still Cover	60
3.4.1.3	Rubber Scrapers	63
3.4.1.4	Electrical Control Circuit Board System	64
3.4.1.5	Miscellaneous Components	66
3.4.2	Test Rig Assembly	71
3.4.2.1	Instrumentation	73
3.4.2.2	Pre-testing	74
3.5	Experimental Test Procedure	74
3.5.1	Saline Water Sample Collection	74
3.5.2	Distilled Water Sample Collection	75
3.5.3	Laboratory Measurement of Water Samples	75
3.5.4	Measurement Instruments for Water Quality	76
3.5.5	Characterization of Saline and Distilled Water	77
3.5.5.1	Turbidity Measurement	77
3.5.5.2	Electrical Conductivity Measurement	77
3.5.5.3	pH Measurement	77
3.5.5.4	Total Dissolved Solids (TDS) Measurement	78
3.5.5.5	Salinity Measurement	78
3.5.5.6	Metals Measurement	78
3.5.5.7	Coliform Bacteria Measurement	81
3.5.5.8	Biochemical Oxygen Demand (BOD) Measurement	82
3.5.5.9	Chemical Oxygen Demand (COD) Measurement	83
3.6	Outdoor Experiments of the Solar Still	84
3.7	Summary	87
4	THEORETICAL ANALYSIS	88
4.1	Introduction	88
4.2	Heat Transfer Mechanism in Solar Still	88
4.3	Energy Balance Equations	88
4.3.1	Energy Balance Equation for Glass Cover	89
4.3.2	Energy Balance Equation for Water	89
4.3.3	Energy Balance Equation for Basin	90

4.4	Internal Heat Transfer	90
4.4.1	Convective Heat Transfer from Water to Glass Cover	90
4.4.2	Radiative Heat Transfer from Water to Glass Cover	92
4.4.3	Evaporative Heat Transfer from Water to Glass Cover	93
4.4.4	Total Internal Heat Transfer Coefficient	94
4.5	Modified Theoretical Modeling of Hourly Yield of the DSSSHS	95
4.6	Proposed Models	96
4.6.1	Regression Model	96
4.6.2	Hybrid Particle Swarm Optimization Algorithm-Hourly Yield of Solar Still (PSO-HYSS) Model	98
4.6.2.1	Objective Function	98
4.6.2.2	Particle Swarm Optimization (PSO) Algorithm	99
4.6.2.3	Convergence Criteria	101
4.6.2.4	Implementing the Particle Swarm Optimization (PSO) Algorithm with HYSS Model	102
4.6.3	Extended Hybrid Particle Swarm Optimization Algorithm-Hourly Yield of Solar Still (PSO-HYSS) Model	105
4.7	Efficiency of the Double Slope Solar Still Hybrid with Rubber Scrapers (DSSSHS)	106
4.8	Error Analysis	107
4.9	Cost Analysis	107
4.10	Summary	108
5	RESULTS AND DISCUSSIONS	109
5.1	Introduction	109
5.2	Experimental Results	109
5.2.1	Optimal Double Slope Solar Still (DSSS) Orientation that Achieves the Highest Yield	109
5.2.2	Performances of Solar Stills	113
5.3	Proposed Models	120
5.3.1	Regression Model	120
5.3.2	Hybrid Particle Swarm Optimization Algorithm-Hourly Yield of Solar Still (PSO-HYSS) Model	132
5.3.2.1	Analysis of the Particle Swarm Optimization Algorithm-Hourly Yield of Solar Still (PSO-HYSS) Model	137
5.3.2.2	Verification of the Particle Swarm Optimization Algorithm-Hourly Yield of Solar Still (PSO-HYSS) Model	142
5.3.2.3	Effect of Solar Radiation on the Productivity of Solar Still	150
5.3.2.4	Error Analysis	151

5.3.3	Extended Hybrid Particle Swarm Optimization Algorithm-Hourly Yield of Solar Still (PSO-HYSS) Model	152
5.3.3.1	Analysis of Extended Particle Swarm Optimization Algorithm-Hourly Yield of Solar Still (PSO-HYSS) Model	162
5.3.3.2	Verification of the Extended Particle Swarm Optimization Algorithm-Hourly Yield of Solar Still (PSO-HYSS) Model	166
5.3.3.3	Effects of Solar Radiation and Number of Scraper Movements per Hour (<i>NSM</i>) on the Productivity of Solar Still	176
5.3.3.4	Error Analysis	178
5.4	Efficiency of the Double Slope Solar Still Hybrid with Rubber Scrapers (DSSSHS)	179
5.5	Cost Analysis	179
5.6	Water Quality	181
5.7	Summary	183
6	CONCLUSIONS AND RECOMMENDATIONS	184
6.1	Conclusions	184
6.2	Recommendations	186
	REFERENCES	187
	APPENDICES	210
	BIODATA OF STUDENT	263
	LIST OF PUBLICATIONS	264

LIST OF TABLES

Table		Page
2.1	Summary of single slope solar still (SSSS-system) enhancement techniques	16
2.2	Summary of double slope solar still (DSSS) system enhancement techniques	20
2.3	Summary of wick type solar still (WTSS)	21
2.4	Summary of multi-effect and tilted tray / stepped solar still system	26
2.5	Summary study of solar still integration techniques with collector systems	33
2.6	Representative ion concentrations for standard seawater and high and low salinity brackish water	51
2.7	Drinking water quality standards	52
3.1	Components of the experimental rig	73
3.2	List of important measurement instrument used during experimentation	74
3.3	Measurement instruments for water quality parameters	76
3.4	Distribution of days used to construct and verify the yield prediction models	86
4.1	Major PSO algorithm parameters	101
4.2	PSO algorithm convergence parameters	101
4.3	Statistical parameters of the proposed models and their validation condition	105
5.1	Comparison of convective, evaporative, and radiative heat transfer coefficients from water to glass cover determined using the regression model, the Dunkle's model, the Kumar and Tiwari's model, and the Clark's model for the DSSSHS	122
5.2	Range of parameters for 87 recorded data sets used to construct the PSO-HYSS model	137

5.3	Comparison of experimental results among the the PSO-HYSS model, regression model, Dunkle's model, Kumar and Tiwari's model, and Clark's model	144
5.4	<i>RRMSE</i> , <i>R</i> , and <i>PI</i> of the PSO-HYSS model, regression model, Dunkle's model, Kumar and Tiwari's model, and Clark's model	148
5.5	Statistical parameters of PSO-HYSS model, regression model, Dunkle's model, Kumar and Tiwari's model, and Clark's model for external validation	149
5.6	Range of parameters for the 207 recorded data sets used to construct the extended PSO-HYSS model	161
5.7	Comparison of the measured and predicted HYSS values for extended PSO-HYSS model, PSO-HYSS model, regression model, Dunkle's model, Kumar and Tiwari's model, and Clark's model	168
5.8	<i>RRMSE</i> , <i>R</i> , and <i>PI</i> of extended PSO-HYSS model, PSO-HYSS model, regression model, Dunkle's model, Kumar and Tiwari's model, and Clark's model	174
5.9	Statistical parameters of extended PSO-HYSS model, PSO-HYSS model, regression model, Dunkle's model, Kumar and Tiwari's model, and Clark's model for external validation	175
5.10	Efficiency of the DSSSHS	179
5.11	Cost estimation for the DSSSHS components	180
5.12	Cost analysis of the DSSSHS	180
5.13	Water quality results compared with standards	182

LIST OF FIGURES

Figure		Page
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)	3
1.2	World water content	5
1.3	Schematic of the problem statement	6
2.1	Classification of solar desalination systems	14
2.2	Schematic of a simple solar still system	15
2.3	Schematic of the modified solar still system and the glass basin	17
2.4	Schematic for the layout of the experimental setup	18
2.5	Schematic of single basin and double basin solar stills	19
2.6	Schematic of the solar still augmented with pin-finned wick evaporation surface	22
2.7	Schematic of cross-sectional view of the corrugated wick solar still system with reflectors	22
2.8	Schematic of the FW-BVMED-HR still	23
2.9	Schematic for the vertical multiple-effect diffusion still coupled with tilted wick still	24
2.10	Schematic of the basin type double slope solar still with different wick materials	25
2.11	Schematic of a 3D view of an inclined solar still with baffle plates	27
2.12	Cross sectional view of a schematic of weir-type cascade solar still	28
2.13	Stand-alone triple basin solar desalination system	29
2.14	Single slope single basin solar still with corrugated absorber plate	30

2.15	Schematic of the experimental set-up for a modified basin type solar still	31
2.16	Schematic of the solar still experimental set-up using nanofluids	32
2.17	Schematic of the multi-effect solar still	34
2.18	Parameters affecting solar still productivity	35
2.19	Variation of solar radiation and still output	37
3.1	Flow diagram describing the investigation sequence of the research study	56
3.2	Investigation tools of solar still modeling	57
3.3	Schematic of the DSSSHS	58
3.4	Image of the fabricated trough	59
3.5	(a) Schematic of the side walls (b) Photograph of the side walls	60
3.6	Image of the fabricated condensing cover	62
3.7	Fabrication process and fabricated condensing cover	63
3.8	Schematic of the rubber scraper	64
3.9	Electrical components of the rubber scraper control system	65
3.10	Connection of various components of the electrical board	65
3.11	Frame support structure for solar still	66
3.12	Insulating materials for the basin, saline water feeding tank, and PVC water hoses	67
3.13	Silicon used to seal the solar still	68
3.14	(a) Collection channels, (b) Collection containers	68
3.15	Feed tank for saline water	70
3.16	Images of the DC motor at different views	71
3.17	Photograph of the experimental test rig	72

3.18	Seawater collected from Pantai Morib sea beach, Selangor, Malaysia	75
3.19	HACH DR/890 Colorimeter	79
3.20	Inductivity Coupled Plasma Optical Emission Spectrometer (ICP-OES Optima 7300 DV) for detection of metals (sodium, potassium, magnesium, and calcium)	80
3.21	Apparatus for coliform bacteria test	81
4.1	Description of velocity and positional updates in the PSO algorithm for the 2D parameter space	100
4.2	Flow chart of the PSO–HYSS model for the estimation of the HYSS	103
5.1	Variations in hourly basin, water, humid air inside the still, glass and ambient temperatures, and hourly yield during daytime for the DSSS in N-S orientation	110
5.2	Variations in hourly basin, water, humid air inside the still, glass and ambient temperatures, and hourly yield during daytime for the DSSS in E-W orientation	111
5.3	Daily yield for the DSSS in E-W and N-S orientations with daily solar radiation for the 4 selected days	113
5.4	Variations in hourly basin, water, humid air inside the still, glass and ambient temperatures, and solar radiation during daytime for the DSSSHS	114
5.5	Variations in hourly basin, water, humid air inside the still, glass and ambient temperatures, and solar radiation during daytime for the DSSS	116
5.6	Comparison between the cumulative hourly experimental productivities for the DSSS and DSSSHS with cumulative hourly solar radiation	118
5.7	X-Y correlation according to this study for the regression model	121
5.8	Variation in convective heat transfer coefficient from water to glass cover (h_{cw}) during daytime according to the regression model, the Dunkle's model, the Kumar and Tiwari's model, and the Clark's model for the DSSSHS	124

5.9	Variation in the total heat transfer coefficient (h_l) according to the regression model, Dunkle's model, Kumar and Tiwari's model, and Clark's model for the DSSSHS during daytime	126
5.10	Hourly variation in the experimental yield for the DSSSHS according to this study and theoretical hourly yields according to regression model, Dunkle's model, Kumar and Tiwari's model, and Clark's model for the DSSSHS	128
5.11	Relation between daily production and daily solar radiation for the DSSSHS	131
5.12	Experimental records for 8 days (87 datasets) used to construct the PSO-HYSS model	133
5.13	Experimental records for 4 days (43 datasets) used to verify the PSO-HYSS model	135
5.14	Convergence for various swarm sizes used in the PSO-HYSS model	139
5.15	Measured versus predicted hourly yields of the DSSSHS based on the PSO-HYSS model	140
5.16	Bland–Altman plot for relationship between measured and predicted hourly yield of the DSSSHS obtained using the PSO-HYSS model	141
5.17	Hourly yield predictions by the PSO-HYSS model, regression model Dunkle's model, Kumar and Tiwari's model, and Clark's model versus the experimentally measured hourly yield	143
5.18	Comparison of measured and predicted HYSS values for the PSO-HYSS model, regression model, Dunkle's model, Kumar and Tiwari's model, and Clark's model	146
5.19	Relationship between daily production of DSSSHS and daily solar radiation	150
5.20	<i>ARE</i> distribution for PSO-HYSS model, regression model, Dunkle's model, Kumar and Tiwari's model, and Clark's model	151
5.21	Experimental records for 19 days (207 data sets) used to construct extended PSO-HYSS model	153
5.22	Experimental records for 5 days (55 data sets) used to verify extended PSO-HYSS model	160

5.23	Convergence for various swarm sizes used in extended PSO-HYSS model	163
5.24	Measured versus predicted hourly yields based on the extended PSO-HYSS model	164
5.25	Bland–Altman plot for the relationship between the measured and predicted HYSS using extended PSO-HYSS model	165
5.26	Hourly yield predictions by extended PSO-HYSS model, PSO-HYSS model, regression model, Dunkle’s model, Kumar and Tiwari’s model, and Clark’s model versus the experimentally measured hourly yield	167
5.27	Comparison of the measured and predicted HYSS values for extended PSO-HYSS model, PSO-HYSS model, regression model, Dunkle’s model, Kumar and Tiwari’s model, and Clark’s model	171
5.28	Relationship between daily production of the DSSSHS and daily solar radiation for various water depths and <i>NSM</i>	176
5.29	Variation of the productivity of the DSSSHS per unit of solar radiation for different <i>NSM</i> and fixed water depth = 0.01 m	177
5.30	<i>ARE</i> distribution for extended PSO-HYSS model, PSO-HYSS model, regression model, Dunkle’s model, Kumar and Tiwari’s model, and Clark’s model	178

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

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
<i>NSM</i>	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

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
VSBS	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. $^{\circ}C$)
$CDWP$	Cost of daily water produced (US\$/kg)
C_g	Specific heat of glass cover (J/kg. $^{\circ}C$)
CoV	Coefficient of variation (%)
C_v	Specific heat of humid air (J/kg. $^{\circ}C$)
C_w	Specific heat of water (J/kg. $^{\circ}C$)
$c_1; c_2$	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
fn	Minimum relative improvement of the value of the objective function
g	Gravitational acceleration (9.807 m/s 2)
g_{best}	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 . $^{\circ}C$)
$h_{c,g-a}$	Convective heat transfer coefficient from glass cover to the ambient (W/m 2 . $^{\circ}C$)
h_{cw}	Convective heat transfer coefficient from water to glass cover (W/m 2 . $^{\circ}C$)
h_{cwCL}	Convective heat transfer coefficient from water to glass cover for Clark's model (W/m 2 . $^{\circ}C$)

h_{cwD}	Convective heat transfer coefficient from water to glass cover for Dunkle's model ($W/m^2 \cdot ^\circ C$)
h_{cwKT}	Convective heat transfer coefficient from water to glass cover for Kumar and Tiwari's model ($W/m^2 \cdot ^\circ C$)
h_{ew}	Evaporative heat transfer coefficient from water to glass cover ($W/m^2 \cdot ^\circ C$)
h_{ewD}	Evaporative heat transfer coefficient from water to glass cover for Dunkle's model ($W/m^2 \cdot ^\circ C$)
h_{fg}	Latent heat of vaporization (J/kg)
$H_g(t)$	Fraction of absorbed solar radiation by the glass cover (W/m^2)
$h_{r,g-sky}$	Radiative heat transfer coefficient from glass cover to the sky ($W/m^2 \cdot ^\circ C$)
h_{rw}	Radiative heat transfer coefficient from water to glass cover ($W/m^2 \cdot ^\circ C$)
h_{rwD}	Radiative heat transfer coefficient from water to glass cover for Dunkle's model ($W/m^2 \cdot ^\circ C$)
$H_w(t)$	Fraction of absorbed solar radiation by the water (W/m^2)
h_I	Total internal heat transfer coefficient ($W/m^2 \cdot ^\circ C$)
h_{ID}	Total internal heat transfer coefficient for Dunkle's model ($W/m^2 \cdot ^\circ C$)
h_{ICL}	Total internal heat transfer coefficient for Clark's model ($W/m^2 \cdot ^\circ C$)
h_{IKT}	Total internal heat transfer coefficient for Kumar and Tiwari's model ($W/m^2 \cdot ^\circ C$)
K	Thermal conductivity of humid air ($W/m.K$)
k_f	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)

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-a}	Heat loss from basin liner to the ambient (W/m ²)
$q_{c,b-w}$	Convective heat transfer rate from basin liner to water (W/m ²)
$q_{c,g-a}$	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)

q_{ewKT}	Evaporative heat transfer rate from water to glass cover for Kumar and Tiwari's model (W/m^2)
$q_{r,g-sky}$	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
$Rand(\cdot)_1;$	Random variables uniformly distributed within range $(0,1)$
$Rand(\cdot)_2$	
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 ($^{\circ}C$)
T_b	Basin temperature ($^{\circ}C$)
TFC	Total fixed cost of the still (US\$)
T_g	Mean glass covers temperature ($^{\circ}C$), (average of T_{g1} and T_{g2})
T_{g1}, T_{g2}	Glass covers temperatures ($^{\circ}C$)
T_v	Vapor temperature; Temperature of humid air inside the still ($^{\circ}C$)
T_w	Water temperature ($^{\circ}C$)
ul	Useful life of the still (year)

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
\hat{y}	Predicted value
\hat{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 ($5.6697 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$)
β	Volumetric thermal expansion coefficient (K^{-1})
ΔT	Temperature difference between water and inner side of glass cover ($^{\circ}\text{C}$)
μ	Dynamic viscosity of humid air ($\text{N}\cdot\text{s/m}^2$)
ρ_v	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

<i>ew</i>	Evaporative
<i>g</i>	Glass
<i>rw</i>	Radiative
<i>v</i>	Vapor
<i>w</i>	Water



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 be 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 CO₂ 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

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.

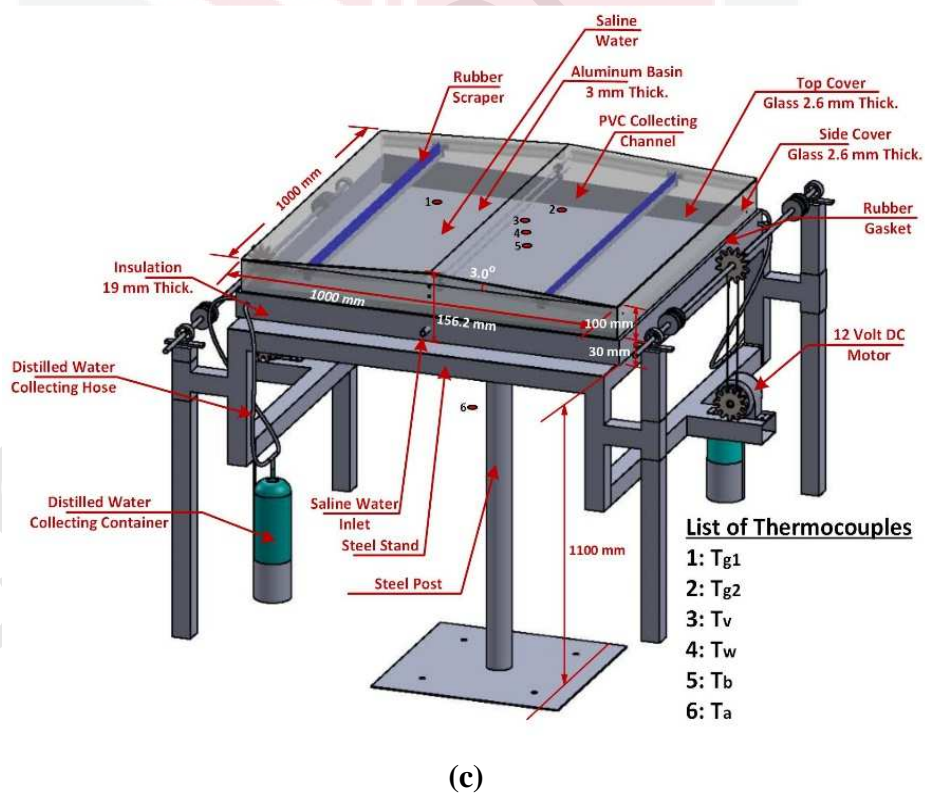
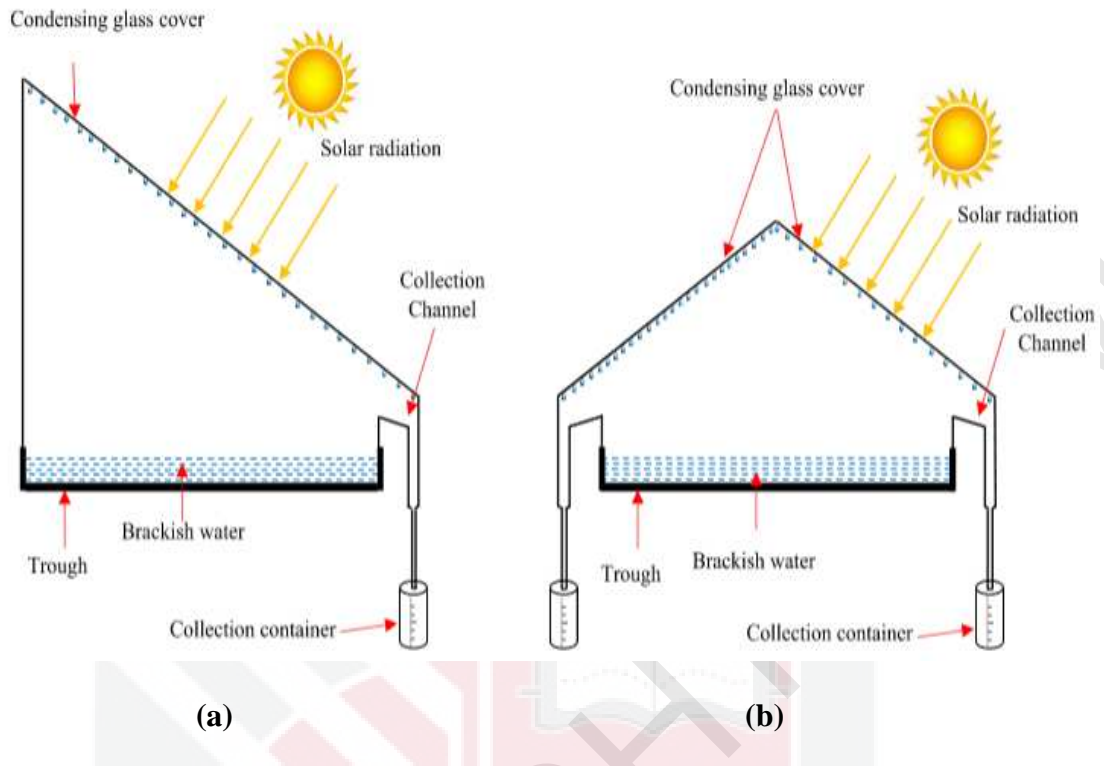


Figure 1.1: Schematic of solar stills: (a) conventional single-slope single-basin solar still, (b) conventional double-slope single-basin solar still, and (c) the proposed design of double-slope solar still hybrid with rubber scrapers (DSSSHS)

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

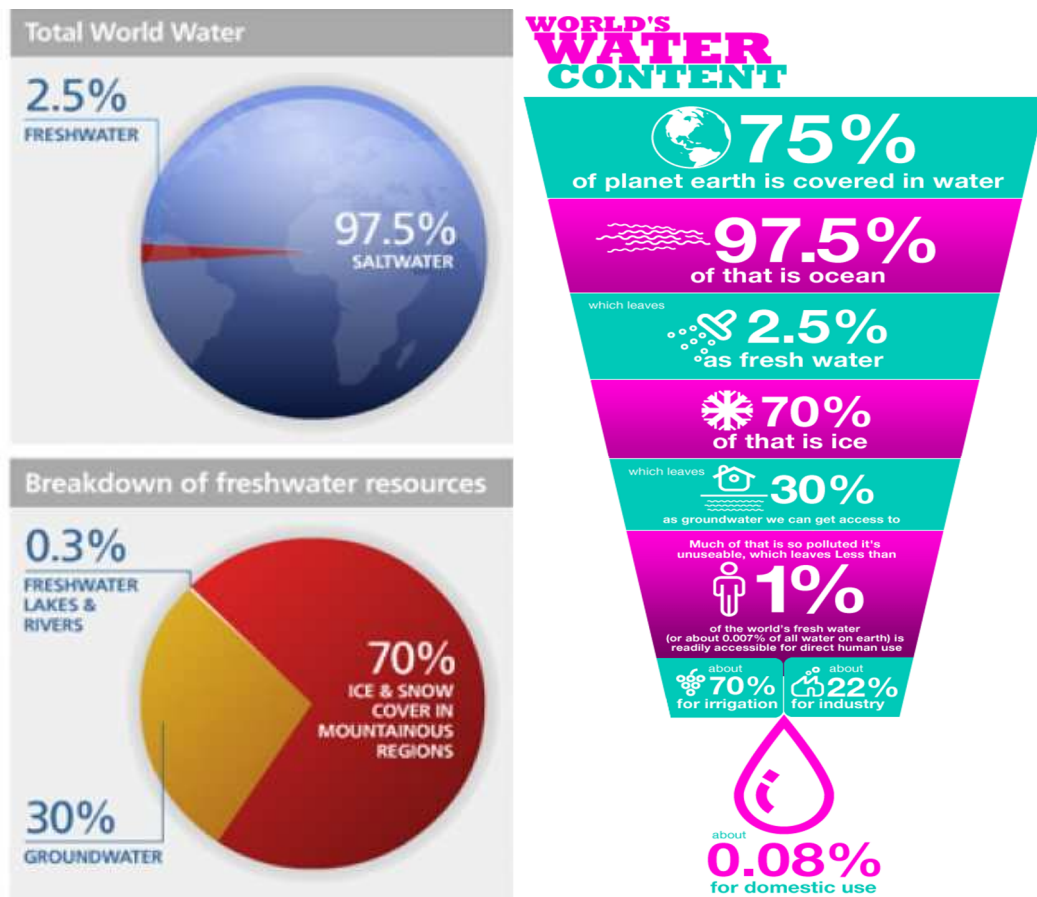


Figure 1.2: World water content (UNEP, 2014)

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.

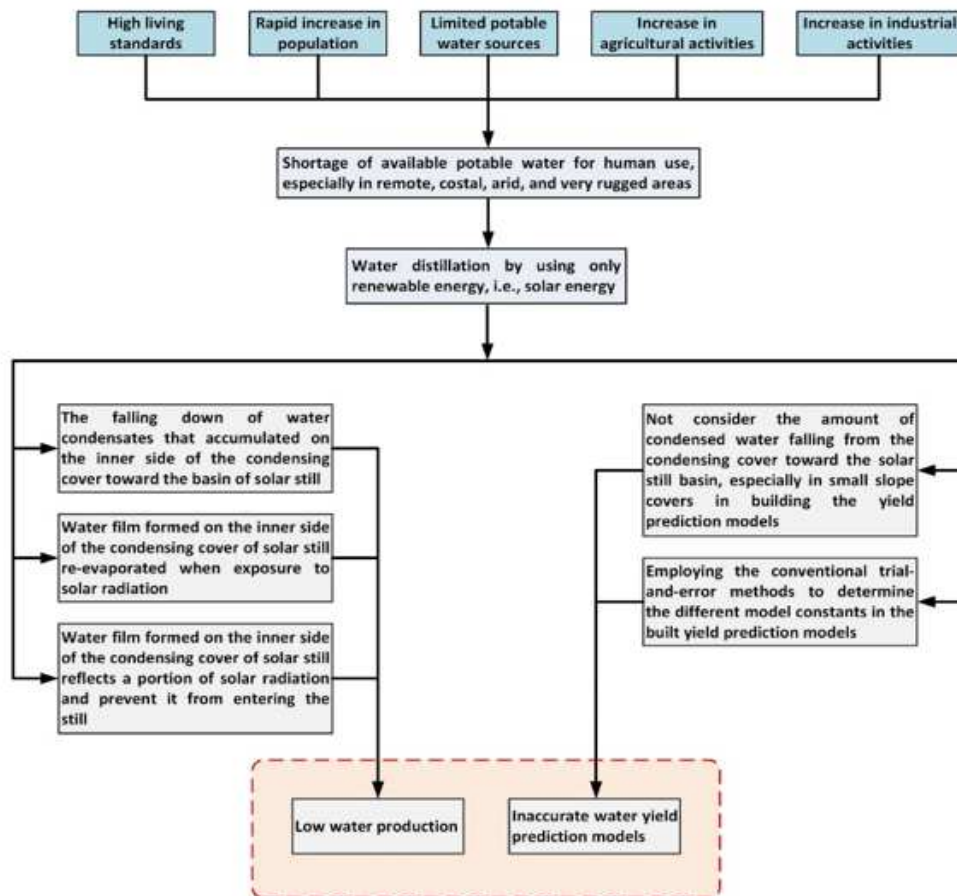


Figure 1.3: Schematic of the problem statement

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.

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 $3^{\circ} 0' 27.71''$, longitude E $101^{\circ} 43' 15.24''$ 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

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 conducted 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.

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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