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Effect of cooling the glass cover of an inclined solar water distillation system under the climatic condition of Riyadh, Saudi Arabia

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ABSTRACT

The decrease of condensed water due to the high temperature of the glass cover is a major setback of an inclined solar water distillation system under the climatic condition of Riyadh, with a summer ambient temperature of more than 45°C at peak time. The small distance between the absorber plate and the top cover glass affects the glass top temperature significantly. In this work, an inclined solar water distillation system was designed, fabricated and tested under the climatic condition of Riyadh to overcome this setback. Thus, this study investigated the effect of cooling the glass cover of an inclined solar water distillation system. The system was tested with three modifications: a system without glass cooling (ISWD), a system with part of the glass shaded with Silver Shade Mesh (SSM) (ISWD-SSM), and a system with intermittent water film (WF) cooling of the glass cover (ISWD-WF). Experimental results show that the use of shade (ISWD-SSM) and water film cooling (ISWD-WF) increased the yield by 10.77% and 58.98%, respectively.

Keywords: Glass cover; Temperature; Water; Film cooling; Silver shade mesh; Absorber plate

1. Introduction

A review of performance, types, efficiencies and influencing parameters of solar distillation systems are available in the literature [1–20]. In the design of any solar distillation system, the temperature difference ($\Delta T_{p\text{-}g}$) between the evaporating plate (T_p) and condensing cover (T_g) determines the productivity [1–3]. The evaporating plate receives solar intensity ($I\alpha\tau$) from the sun to raise its temperature. The amount of solar energy received by the absorber plate depends on the glass cover transmissivity (α) and its absorptivity (τ). The gained heat (in the inclined systems – the intermittent flowing water film) is then transferred to the flowing water on the surface of the absorber plate to induce evaporation (T_m) that is collected on the glass cover surface after condensation. The T_g should be less than the T_m for condensation to happen on the glass cover (Fig. 1). A large temperature difference ($\Delta T_{p\text{-}g}$) between the T_p and T_g increases the distillate output, while a small temperature difference decreases the distillate production. Increasing the temperature difference between the absorber plate of an inclined solar water distillation system and the top glass cover will impact the performance of the system positively.

Solar stills can be categorised as either passive or active. A passive solar still utilised only solar energy for potable water extraction from the sea or brackish water. A conventional passive solar still employs solar radiation to evaporate the stationary or stagnant water in its cavity for the production of distillate output. Utilising a passive method reduces the mechanical components of the system, influences the efficiency of the system and reduces or maintains the cost price of the distillate and the system itself. Some passive methods have been deployed over the years to increase the temperature difference between the evaporating plate and condensing cover of a solar distillation system [17–25]. Abu-Hijleh [17], Tiwari and Rao [18] and Lawrence et al. [19], have all carried out important theoretical studies on conventional passive solar stills to determine the effect of water flowing over the glass cover. On the other hand, an active solar still employed additional thermal energy from

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external sources [26–30]. Developing an active mechanism to achieve this purpose will increase the cost of the system, the routine maintenance, require higher skill from the user and may influence the cost price of the distillate.

However, solar stills can also be classified based on the uniqueness of their design, as (i) Single basin solar stills (ii), Inclined solar stills, and (iii) Multi-basin solar stills [1–7].

An inclined solar distillation system is a still inclined at some angle to the horizontal surface and the water film flow on the absorber plate. The design concept is aimed at increasing rate of evaporation leading to higher production by positioning the still at an effective angle to receive maximum energy from the sun, reducing reflection and increasing the effective area of the system. An inclined solar distillation system performs better when compared with a single basin solar still [1–5,7–8,36]. Kalidasa et al. [31] recapped the following qualities of an inclined solar distillation system: i. Increases system efficiency due to the basin angle to the horizontal surface; ii. Due to the thin layer of the water film on the absorber plate, evaporation occurs faster.

In Saudi Arabia, solar still types, important parameters, economics and performance have been studied. Table 1 shows all the published work on solar stills as obtained from the web of science using "Solar Still" or "Solar Distillation" or "Inclined solar water Distillation" in the search box web of science. The search word "Solar still" was used in the web-of-knowledge search engine. It returns 823 papers consisting of Articles (700), proceeding paper (117), Review (36), Note (11) and Conference Abstract (11) with the first three countries/Territories wise distributions as follows India (306), Egypt (93), Saudi Arabia (49).

Increasing the search criteria to include "Solar still" or "Solar Distillation" or "Inclined solar water Distillation" simultaneously. The search engine returns 984 papers consisting of Articles (830), proceeding paper (145), Review (43), Note (14) and Conference Abstract (16), letter (6) correction (2) editorial material (1) and a book review (1). The first three countries/Territories wise distributions are as follows India (333), Egypt (99), Saudi Arabia (56). For Saudi Arabia, the 56 publications were reviewed regarding the aim of the paper as seen in Table 1. None of the above researchers have performed an experimental analysis of solar still or inclined solar water desalination to test for the effect of shading or water film cooling on the top cover glass of the system. Although other researchers outside Saudi Arabia have documented their finding on the same subject matter [1,2,4–31,87–95], the result varies from one researcher to the other. Table 2 shows a summary of research findings on the cooling of top glass cover of a solar still. The effect of water cooling increases the output from 8% to about 40% [87–95], while Bhardwaj et al. 2013 [95] reported that phenomena such as dropwise/filmwise condensation, inclination angle and wiping did not have a significant effect on the production of water from a solar still.

Hence, in this work, two identical inclined solar water distillation systems were designed and tested under the climatic condition of Riyadh, Saudi Arabia. To investigate the effect of glass cover cooling, one of the systems was set as the control system, while the cooling was performed on the other system. Both systems were tested concurrently during the summer period of 2015. Two glass cover-cooling methods were used: (a) cooling with water film (WF) and (b) shading of part of the glass cover with the Silver Shade Mesh (SSM). To fully understand the system, the findings of the systems' productivity with and without cooling were presented. Solar radiation incidences for the city of Riyadh were presented, and the system efficiencies were determined.

2. Experimental Set up

Fig. 2 shows the schematic diagram of the inclined solar distillation system. The system consisted primarily of an absorber plate, glass cover, distilled water collector channel, distribution pipe fitted with spray jets (nozzles) and a water

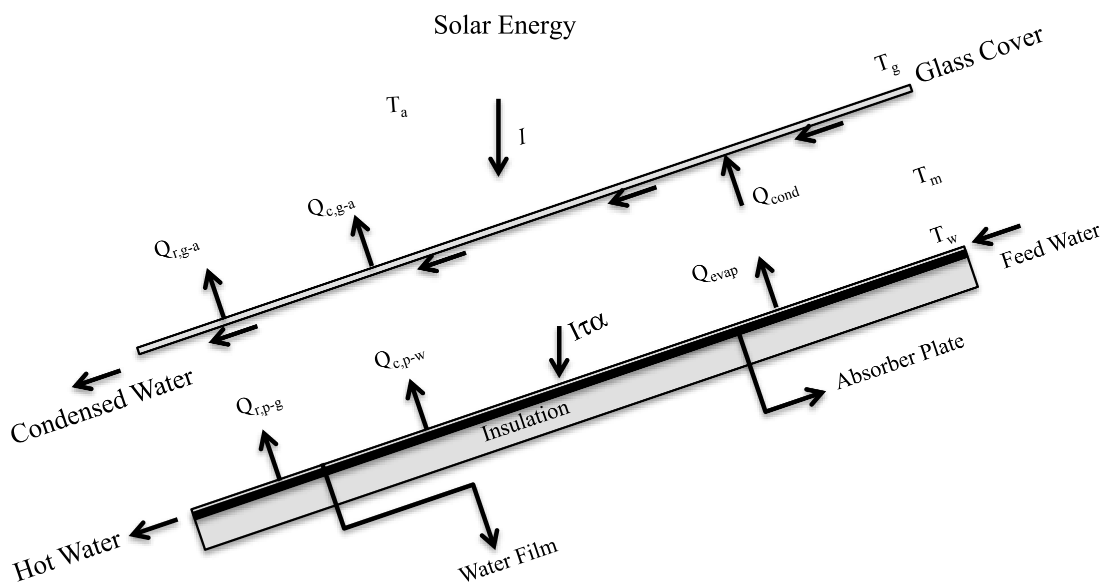

Fig. 1. Thermal processes of an inclined solar water desalination system.

Table 1
Status of solar stills in Saudi Arabia from 1990–2016

No	Author(s)/ References	Title	Methodology	Experimental site/location	Remarks
1	Shalaby et al., 2016 [32]	An experimental investigation of a v-corrugated absorber single-basin solar still using PCM	Experiment	Egypt	A new design of a v-corrugated absorber solar still with built-in phase change material (PCM) is presented.
2	Mashaly and Alazba , 2016 [33]	Neural network approach for predicting solar still production using agricultural drainage as a feed water source	Numerical with data input of Saudi Arabia	–	The study investigates the application of artificial neural network (ANN) for predicting solar still production (MD).
3	Elminshawy et al. 2016 [34]	Development of an active solar humidification-dehumidification (HDH) desalination system integrated with geothermal energy	Experimental	Saudi Arabia	The paper investigates the technical and economic feasibility of using a hybrid solar-geothermal energy source in a humidification-dehumidification (HDH) desalination system.
4	Singh et al. 2016 [35]	Effect of energy matrices on life cycle cost analysis of passive solar stills	Numerical with data input of India	–	The paper presents the life cycle cost analysis of passive solar stills by incorporating the effect of energy payback period. Exergoeconomic and energy matrices have been evaluated for the climatic condition of New Delhi.
5	Mashaly et al. 2016 [36]	Assessing the performance of solar desalination system to approach near-ZLD under hyper-arid environment	Experiment	Saudi Arabia	The aim of this study was to investigate the performance of a solar desalination system using three different types of feedwater to reach near zero liquid discharge (ZLD) under hyper-arid environment. Solar still was used to desalinate seawater (SW), groundwater (GW), and agricultural drainage water (DW).
6	Singh et al. 2016 [37]	Experimental studies of active solar still integrated with two hybrid PVT collectors	Experiments	India	The paper deals with the experimental studies and performance analysis of partially covered hybrid photovoltaic thermal (PVT) flat plate collector (FPC) solar still. The thermal model of the system has been developed.
7	Kabeel et al. 2016 [38]	Solar still with condenser – A detailed review	Theoretical	–	In this comprehensive survey, we are seeking to introduce, explain and discuss the status of different solar stills integrated with various condensers arrangements.
8	Mashaly and Alazba , 2016 [39]	MLP and MLR models for instantaneous thermal efficiency prediction of solar still under hyper-arid environment	Numerical with input data of Saudi Arabia	–	The purpose of this study was to determine the viability of modeling the instantaneous thermal efficiency (eta(ith)) of a solar still, using weather and operational data with Multi-Layer Perceptron (MLP) neural network and multiple linear regressions (MLR).
9	Omara et al. 2016 [40]	Experimental investigation of corrugated absorber solar still with wick and reflectors	Experimental	Egypt	The performance parameters of the corrugated solar still (CrSS) and conventional solar still (CSS) are investigated experimentally from another point of view. The authors' view concerns with using the double layer wick material and also reflectors together inside the CrSS.
10	Zarzoum et al. 2016 [41]	Numerical study of a water distillation system using solar energy	Numerical with data input of Egypt	–	This optimization approach is based upon the above-mentioned design's improvement by coupling the conventional solar still into at a condenser, solar air and water collector and humidifier. This new concept of a distiller solar still using humidification-dehumidification processes (HD) is exploited for the desalination purpose.

(Continued)

Table 1 *(Continued)*

No	Author(s)/ References	Title	Methodology	Experimental Site/Location	Remarks
11	Mashaly and Alazba , 2016 [42]	Comparison of ANN, MVR, and SWR models for computing thermal efficiency of a solar still	Numerical with data input from Saudi Arabia	–	In the paper, the viability of modeling the instantaneous thermal efficiency of a solar still was determined using meteorological and operational data with an artificial neural network (ANN), multivariate regression (MVR), and stepwise regression (SWR).
12	Mashaly and Alazba , 2015 [43]	Comparative investigation of artificial neural network learning algorithms for modeling solar still production	Numerical with data input from Saudi Arabia	–	Three artificial neural network learning algorithms were utilized to forecast the productivity (MD) of a solar still operating in a hyper-arid environment.
13	Matrawy et al. 2015 [44]	Modeling and experimental study of a corrugated wick type solar still: Comparative study with a simple basin type	Numerical and Experimental	Saudi Arabia	In the present work, the productivity of a solar still is modified by forming the evaporative surface as a corrugated shape as well as by decreasing the heat capacity with the use of a porous material. This target has been achieved by using black clothes in a corrugated shape that are immersed in water where the clothes absorbs water and get saturated by capillary effect
14	El-Sebaii and El-Bialy 2015 [45]	Advanced designs of solar desalination systems: A review	Theoretical	–	In this paper, a review of different designs of solar stills was presented mainly the double, triple and multi-effect solar stills, vertical stills, tubular type solar stills, finned and corrugated stills, and stepped type solar stills. A detailed cost analysis for different configurations was presented. The various parameters affecting the performance of the considered designs of solar stills were outlined.
15	Mashaly at el 2015 [46]	Predictive model for assessing and optimizing solar still performance using artificial neural network under hyper-arid environment	Numerical with input data from Saudi Arabia	–	A mathematical model to forecast the solar still performance under hyper arid conditions was developed using artificial neural network technique. The developed model expressed by different forms, water productivity (MD), operational recovery ratio (ORR) and thermal efficiency requires ten input parameters.
16	Tiwari et al. 2015 [47]	Exergoeconomic and enviro-economic analyses of partially covered photovoltaic flat plate collector active solar distillation system	Experimental	India	This paper presents an exergoeconomic and enviroeconomic analyses of partially covered photovoltaic thermal (PVT) flat plate collector (FPC) integrated solar distillation system known as PVT-FPC active solar distillation system. The report is based on experimental studies for the composite climatic condition of New Delhi.
17	Elminshawy, et al. 2015 [48]	Experimental and analytical study on productivity augmentation of a novel solar humidification-dehumidification (HDH) system	Experimental	Saudi Arabia	The aim of this study is to investigate analytically and experimentally the effect of using an induced atmospheric air, water heaters, external reflector and weather condition on the performance augmentation of humidification-dehumidification (HDH) system
18	Mashaly 2015 [49]	Area determination of solar desalination system for irrigating crops in greenhouses using different quality feed water	Experimental and Numerical	Saudi Arabia	The aim of this study was to present an alternative means of procuring fresh water from low-quality water sources to meet crop-water requirements (CWR) in greenhouses. A solar still was used in field experiments to desalinate three types of water: seawater, ground water and agricultural-drainage water

(Continued)

Table 1 *(Continued)*

No	Author(s)/ References	Title	Methodology	Experimental Site/Location	Remarks
19	Ayoub et al. 2015 [50]	A solar still desalination system with enhanced productivity	Experiments	Not stated	This paper describes a sustainable modification of the solar still that significantly enhances its productivity without forsaking its core features. A simple amendment in the form of a slowly rotating drum is introduced allowing the formation of thin water films that evaporate rapidly and are continually renewed.
20	Agboola et al. [3]	Thermo-economic performance of Inclined Solar Water Distillation Systems	Experimental	Cyprus	This study investigates the thermo-economic performance of different configurations at inclined solar water desalination for parameters such as daily production, efficiency, system cost, and distilled water production cost.
21	El-Samadony et al. 2015[51]	Experimental study of stepped Solar still integrated with reflector and external condenser	Experimental	Egypt	In this article, an experimental study of a modified stepped solar still with internal and external reflectors and an external condenser is presented.
22	Al-Garni 2014 [52]	Productivity enhancement of single slope solar still using immersion-type water heater and external cooling fan during summer	Experimental	Saudi Arabia	In this paper, an attempt is made to study the productivity enhancement of a single-slope solar still using an immersion-type water heater and external cooling fan.
23	Zarzoum et al. 2014 [53]	Improving the design, modeling and simulation in dynamic mode of a solar still	Experimental and Numerical	Not stated	In the present work, we propose to establish a mathematical model reflecting the operation of a solar still. The proposed research is to improve the production of a solar still by making changes in the design of the conventional solar still by adding a trim-level distiller which plays the role of a humidifier, a pulverizer, and a condenser to study the effect of internal and external parameters of the operation of a solar still.
24	Ayoub et al. 2014 [54]	Vapor-induced transfer of bacteria in the absence of mechanical disturbances	Experimental	Lebanon	The objective of this research was to investigate whether bacteria in highly humid atmospheres can get transferred through water vapor in the absence of other transfer media to find their way to the distillate.
25	El-Bialy E. 2014 [55]	Performance analysis for passive single slope single basin solar distiller with a floating absorber – An experimental study	Experimental	Egypt	In this work, a detailed comparison between the thermal performance of single slope single basin solar distiller (SBD) and single slope single basin solar distiller with a floating absorber (SBDFA) has been investigated.
26	Al-Garni AZ 2014 [56]	Effect of External Reflectors on the Productivity of a Solar Still During Winter	Experimental and Numerical	Saudi Arabia	This paper presents the experimental work carried out in winter for a double slope solar still with external reflectors. Experiments were performed in Dhahran, a city in the eastern province of Saudi Arabia at latitude 26 degrees N. Four inclined mirrors were placed around the still to reflect extra solar irradiance onto the solar still. Numerical analysis was also carried out using heat and mass transfer inside the solar still and was validated with the experimental results. The external reflectors were shown to significantly enhance the productivity of the solar still, and an increase in the distillate by approximately 82% was observed in this study. The present study is a partial implementation of two patents submitted recently in the field of solar distillation.

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Table 1 *(Continued)*

No	Author(s)/ References	Title	Methodology	Experimental Site/Location	Remarks
27	Ayoub and Malaeb, 2014 [57]	Economic feasibility of a solar still desalination system with enhanced productivity	Experimental	Lebanon	In this study, a simple amendment, in the form of a slowly-rotating hollow cylinder, was introduced within the solar still, significantly increasing the evaporative surface area. This new modified still was analyzed regarding both operation and economic feasibility.
28	Malaeb et al. 2014 [58]	The Effect of Cover Geometry on the Productivity of a Modified Solar Still Desalination Unit	Experimental	Lebanon	A new modification has been introduced to the conventional solar still to enhance its productivity. The modification consists of a light weight, black finished, slowly-rotating drum, which leads to a sustainable, cost-effective, and low-tech amendment that preserves the essential features of the still while considerably increasing its yield compared to a control still that does not include the drum.
29	Ayoub et al. 2013 [59]	Critical variables in the performance of a productivity-enhanced solar still	Experimental	Lebanon	The introduced modification is in the form of a slowly rotating hollow drum within the still cavity that allows the formation of thin water films, which evaporate rapidly and cover cooling using fan – generated the wind
30	Abdullah 2013 [60]	Improving the performance of stepped solar still	Experimental	Egypt	In this paper, the experimental performance of a stepped solar still coupled with a solar air-heater was investigated. A single slope passive solar still (conventional still) and stepped active solar still integrated with a solar air-heater collector were fabricated with an area of 0.5 m (2).
31	Bacha and Zhani 2013 [61]	Contributing to the improvement of the production of solar still	Numerical	–	In this work, an energy storing material is used in the basin, a flat plate solar collector and a separate condenser are coupled with the solar still to increase the daily productivity by increasing the temperature of the water during the day and to store the hot water excess that would extend water desalination beyond sunset. The models of the different sections of the unit are developed from the governing heat and mass transfer equations.
32	Al-Garni 2013 [62]	Productivity Enhancement of Solar Still Using Water Heater and Cooling Fan	Experimental/ Numerical	Saudi Arabia	In the present work, an attempt is made to enhance the productivity of a double slope solar still by using an immersion type water heater. The effect of using an external fan to cool the glass surface is also examined. When the external cooling fan was used, the productivity was found to decrease by 4% and 8% for wind speeds of 7 m/s and 9 m/s, respectively.
33	Taamneh and Taamneh 2012 [63]	Performance of pyramid-shaped solar still: Experimental study	Experimental	Jordan	In this study, the effect of forced convection on the performance of pyramid-shaped solar still is investigated experimentally under outdoors of Tafila City (south of Jordan) climatic conditions.
34	Ayoub and Malaeb 2012 [64]	Developments in Solar Still Desalination Systems: A Critical Review	Theoretical	–	The authors present a critical review of the research work conducted on solar stills development. Studies addressing each parameter of concern are grouped together and results compared. Novelty in design and newly introduced features are presented. Modeling efforts of flow circulation within the still and methods to estimate internal heat transfer coefficients are discussed, and future research needs are outlined.

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Table 1 *(Continued)*

No	Author(s)/ References	Title	Methodology	Experimental Site/Location	Remarks
35	El-Sebaii and Shalaby 2012 [65]	Solar drying of agricultural products: A review	Theoretical	–	Solar energy applications were divided mainly into two categories: the first is the direct conversion to electricity using solar cells (electrical applications). The second is the thermal applications. The latter include solar heating, solar cooling, solar drying, solar cooking, solar ponds, solar distillation, solar furnaces, solar-thermal power generation, solar water heating, solar air heating, etc.
36	Sharqawy et al. 2011 [66]	Second law analysis of reverse osmosis desalination plants: An alternative design using pressure retarded osmosis	Numerical	–	A second law analysis of a reverse osmosis desalination plant is carried out using reliable seawater exergy formulation instead of a common model in literature that represents seawater as an ideal mixture of liquid water and solid sodium chloride.
37	Al-Garni et al. 2011 [67]	Effect of glass slope angle and water depth on productivity of double slope solar still	Experimental	Saudi Arabia	This study presents design, fabrication and testing of double slope solar still and also optimization of glass tilt angle (25, 30, 35 and 40 degrees) and water depth (1, 2 and 3 cm) in Saudi Arabian climatic conditions
38	El-Sebaii 2011 [68]	On effect of wind speed on passive solar still performance based on inner/outer surface temperatures of the glass cover	Numerical with data input of Saudi Arabia	–	The thermal performance of a passive single basin solar still was investigated by computer simulation using the climatic conditions of Jeddah (lat. 21 degrees 42′ N, long. 39 degrees 11′ E), Saudi Arabia
39	El-Sebaii and Al-Dossari 2011 [69]	A mathematical model of single basin solar still with an external reflector	Numerical with data input of Saudi Arabia	–	A transient mathematical model was presented for a single basin solar still with and without an external reflector.
40	Antar and Zubair 2010 [70]	Performance evaluation of a solar still in the Eastern Province of Saudi Arabia – an improved analysis	Numerical with data input of Saudi Arabia	–	The performance of a solar still is predicted though an improved and updated mathematical model.
41	Kabeel et al. 2010 [71]	Cost analysis of different solar still configurations	Theoretical	–	The primary objective of this work is to estimate the water production cost for various types of solar stills. In this paper, 17 design configurations are considered.
42	El-Sebaii et al. 2009 [72]	Active single basin solar still with a sensible storage medium	Numerical with data input of Saudi Arabia	–	Transient mathematical models are presented for an active single basin solar still (ASS) with and without a sensible storage material under the basin liner of the still. Sand is used as a storage material due to its availability.
43	El-Sebaii et al. 2009 [73]	Thermal performance of a single basin solar still with PCM as a storage medium	Numerical with data input of Saudi Arabia	–	Transient mathematical models are presented for a single slope-single basin solar still with and without phase change material (PCM) under the basin liner of the still. Analytical expressions for temperatures of the still elements and the PCM have been obtained.
44	Radhwan, and Fath 2005 [74]	Thermal performance of greenhouses with a built-in solar distillation system: experimental study	Experimental and Numerical	Saudi Arabia	An experimental investigation is presented of the thermal performance of an agricultural greenhouse (GH) with a built-in solar distillation system.

(Continued)

Table 1 *(Continued)*

No	Author(s)/ References	Title	Methodology	Experimental Site/Location	Remarks
45	Radhwan 2005 [75]	Transient performance of a stepped solar still with built-in latent heat thermal energy storage	Numerical with data input of Saudi Arabia	–	The transient performance of a stepped solar still with built-in latent heat thermal energy storage was studied. The still was designed for heating and humidification of agriculture greenhouses (GH) in remote areas.
46	Radhwan 2004 [76]	Transient analysis of a stepped solar still for heating and humidifying greenhouses	Numerical with data input of Saudi Arabia	–	This paper presents the transient analysis of a stepped solar still for heating and humidifying agriculture greenhouses (GH).
47	Hasnain and Alajlan 1998 [77]	Coupling of PV-powered RO brackish water desalination plant with solar stills	Theoretical	–	To utilize inland reserves of brackish water by the local inhabitants, the Energy Research Institute (ERI) of King Abdulaziz City for Science and Technology (KACST) installed a photovoltaic- (PV) powered water desalination reverse osmosis (RO) plant in Riyadh, Saudi Arabia. The reject brine rate from this plant is very high. Due to the inherent advantages of solar still assemblies, for instance; simple to construct and maintain using locally available materials, and high technical feasibility in remote areas, a solar still plant capacity of 5.8 m^3 distillate per day is proposed to couple with the existing PV-RO plant in order to utilize most of the reject brine instead of releasing it into the ground.
48	Hasnain and Alajlan 1998 [78]	Coupling of PV-powered RO brackish water desalination plant with solar stills	Theoretical	–	To utilize inland reserves of brackish water by the local inhabitants, the Energy Research Institute (ERI) of King Abdulaziz City for Science and Technology (KACST) installed a photovoltaic- (PV) powered water desalination reverse osmosis (RO) plant in Riyadh, Saudi Arabia. The reject brine rate from this plant is very high. Due to the inherent advantages of solar still assemblies, for instance; simple to construct and maintain using locally available materials, and high technical feasibility in remote areas, a solar still plant capacity of 5.8 m^3 distillate per day is proposed to couple with the existing PV-RO plant in order to utilize most of the reject brine instead of releasing it into the ground.
49	Abdelrassoul 1998 [79]	Potential for economic solar desalination in the Middle East	Theoretical	–	Review of desalination systems
50	Fath 1996 [80]	High performance of a simple design, two effects solar distillation unit	Numerical with data input of Saudi Arabia	–	Under a passive mode of operation, a transient analysis of a new, simple design, two effects solar distillation unit is presented.
51	Madani and Zaki 1995 [81]	Yield of Solar stills with porous basins	Experimental	Saudi Arabia	The effects of the powder and the basin's insulation layer on the yield from the solar still are examined experimentally.
52	Gandhidasan and Abualhamayel 1994 [82]	A simple analysis of Solar desalination of sea water	Numerical with data input of Saudi Arabia	–	A tilted solar still has been studied in application to desalinate the seawater.
53	Abuabdou 1994 [83]	Analysis of continuous-flow thin film solar stills	Numerical with data input of Saudi Arabia	–	A continuous-flow thin-film solar still is analysed. Both fluid dynamics of the thin-film flow and first law analysis of the system are included.

(Continued)

Table 1 *(Continued)*

No	Author(s)/ References	Title	Methodology	Experimental Site/Location	Remarks
54	Fatani et al. 1994 [84]	Improving the yield of simple basin solar stills as assisted by passive cooled condenser	Experimental/ Numerical	Saudi Arabia	The present analysis, based on actual meteorological data, shows that the yield improvement depends upon the heat removal rate by the condenser and brine depth that determines the thermal inertia of the still. The yield has been measured for a still coupled to a passively cooled condensing plate, made of aluminium sheets with 2 cm gap allowing for natural convection of atmospheric air.
55	Zaki et al. 1993 [85]	Analysis of assisted coupled solar stills	Numerical with data input of Saudi Arabia	–	The potential of coupled solar stills as a mean for improving solar distillation yield is investigated. A model for a simple solar still assisted by an external solar collector is presented.
56	Fath and Elsherbiny 1993 [86]	Effect of adding a passive condenser on solar still performance	Experimental/ Numerical	Egypt	A theoretical and experimental study was conducted to investigate the effect of adding a passive condenser on the performance of the single slope, basin type solar still. A theoretical model based on the Dunkle (Int. Devs Heat Transfer 5, 895 (1969); Ref. [1]) mass transfer (evaporation) rate was developed.

Table 2
Some selected works on effect of top glass cover cooling on solar still performance

No	Authors/ References	Title	Methodology	Findings
1	Gupta et al. 2016 [87]	Performance enhancement of modified solar still using water sprinkler: An experimental approach	The use of water sprinkler for cooling the top cover glass	The distilled water output was recorded 2940 ml and 3541 ml from conventional and modified solar stills respectively. Water productivity or yield of single slope solar still is increased by 20% from above modifications. The overall efficiency increased by 21% over the conventional solar still
2	Abu-Hijleh & Mousa 1997 [88]	Water film cooling over the glass cover of a solar still including evaporation effects	Water film on top glass cover was numerically investigated	The effect of water film cooling of the glass cover on the efficiency of a single-basin still has been investigated numerically. Proper use of the film-cooling parameters may increase the still efficiency by up to 20%
3	Lawrence et al. 1990 [89]	Effect of heat capacity on the performance of solar still with water flow over the glass cover	Water film on top glass cover was numerically and experimentally investigated	There is a 7 and 10% increase in efficiency of the solar still due to water flow over the glass cover in the cases with and without black dye present in the basin of the solar still
4	El-Samadony & Kabeel 2014 [90]	Theoretical estimation of the optimum glass cover water film cooling parameters combinations of a stepped solar still	Water film on top glass cover was numerically investigated	The performance evaluation of a stepped solar still with film cooling was theoretically investigated. The effect of water film cooling thickness, the volumetric flow rate of productivity is studied. The cooling film increases the stepped still daily distillate productivity by about 8.2 percent.
5	Janarthanan et al. 2006 [91]	Performance of floating cum tilted-wick type solar still with the effect of water flowing over the glass cover	Water film on top glass cover was numerically and experimentally investigated	Glass cover temperature decreases significantly due to the water flowing over the glass cover which causes fast evaporation during peak sunny hours. The effect of water flowing over the glass cover has a fascinating role on the performance of the still.
6	Tiwari & Rao 1984 [18]	Transient performance of a single basin solar still with water flowing over the glass cover	Water film on top glass cover was numerically investigated	A simple transient theory of a single basin solar still which includes the effect of water flowing over the glass cover is presented. The daily distillate production of the system is almost doubled by lowering the temperature of the glass cover by water flowing over it at a uniform velocity.

(Continued)

Table 2 *(Continued)*

No	Authors/ References	Title	Methodology	Findings
7	Morad et al. 2015 [92]	Improving the double slope solar still performance by using flat-plate solar collector and cooling glass cover	Water cooling of top glass was investigated among other parameters in a double slope still coupled with a solar collector.	Water temperature, as well as both internal and external temperatures of the glass cover added to ambient temperature, was measured with hour intervals, under all experimental conditions, for both solar stills. The performance of both solar stills was studied as a function of the change in basin brine depth and glass cover thickness under conditions of applying glass cover cooling (flash tactic) or without cover cooling. The performance of solar stills was evaluated regarding recorded temperatures, instantaneous and internal thermal efficiencies and system productivity. The experimental results revealed that active solar still maximizes both fresh water productivity (10.06 $l/m^2 \cdot day$) as well as internal thermal efficiency (80.6%) compared with passive solar still (7.8 $l/m^2 \cdot day$ productivity and 57.1% internal efficiency) under conditions of 1 cm basin brine depth and 3 mm glass cover thickness and by applying flash tactic cover cooling with 5 min on and 5 min off.
8	Dhiman & Tiwari,1990 [93]	Effect of water flowing over the glass cover of a multi-wick solar still	Water film on top glass cover was numerically investigated	It shows that the distillate is more in the case when water is flowing over the glass cover in a very thin layer. The reason for this is the increased difference between the temperatures of the water in the still and the glass cover. The output is increased by approx. 10%.
9	El-Sebaii 2011 [68]	On effect of wind speed on passive solar still performance based on inner/outer surface temperatures of the glass cove	Cooling of the top glass cover using increase wind was numerically investigated	Effect of wind speed on the productivity of a single basin solar still was studied. The inner surface temperature of the still cover strongly affects the still performance.
10	Deniz 2012, [1]	An investigation of some of the parameters involved in inclined solar distillation systems	Top cover glass cooling using shading method was experimentally investigated	The system was tested with four variants: bare plate (BP), shaded bare plate (SBP), black-cloth wick (BCW), and shaded black-cloth wick (SBCW). Experimental studies showed that the use of bare cloth wick, shading plate, and both together increase the system efficiency by 3, 2, and 5% respectively.
11	Bechki et al. 2010 [94]	Effect of partial, intermittent shading on the performance of a simple basin solar still in South Algeria	Top cover glass cooling using intermittent shading method was experimentally investigated	Three series of experiments were performed. The first consisted of studying the solar still under local climatic conditions. The bottom and the sides of the still were lagged with an additional 100 mm insulation layer of local dune sand in the second series. The daily output in the first series was found 6.01 $L/(m^2\ d)$. This amount was improved in the second series by about 33.7%. The third series consisted of lowering the glass temperature, by an intermittent shading of the north glass cover. This procedure resulted in a further 12% enhancement in the daily distillate output.
12	Bhardwaj et al. 2015 [95]	Maximized production of water by increasing area of condensation surface for solar distillation	External cooling of the top glass cover was investigated experimentally.	The increase in condensation area has a significant effect on the production of water from solar stills. The results of this study show that the production of water from the still increased by more than five times by increasing the area of the condensation surface from 0.08 m^2 to 0.52 m^2. In the experiments conducted under the sun, the amount of water increased by more than 50% by using the additional area for condensation when compared with a reference still without an additional area of condensation.

(Continued)

Table 2 *(Continued)*

No	Authors/ References	Title	Methodology	Findings
13	Bhardwaj et al. 2013 [24]	Influence of condensation surface on solar distillation	Cooling of the top glass cover using dropwise and filmwise condensation was experimentally investigated	Other phenomena such as dropwise/filmwise condensation, inclination angle and wiping did not have a significant effect on the production of water from a solar still.
14	Abu-Hijleh 1996 [17]	Enhanced solar still performance using water film cooling of the glass cover	Water film on top glass cover was experimentally investigated	The results of this investigation indicate that proper use of film cooling parameters can increase the still efficiency by as much as 6 percent, but poor combinations of film cooling parameters can lead to significant reductions in efficiency of the still.

Fig. 2. A pictorial diagram of the inclined solar distillation system (control system - ISWD).

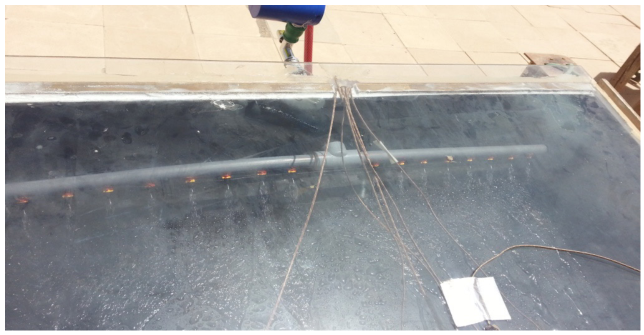

Fig. 3. Distribution pipe fitted with nozzles.

tank for the feed water. The system cavity or frame was constructed from wood (double as the system frame and insulation of 30 mm thickness) with the inside lined with stainless steel sheet; length, width, and height of 1.1 m, 0.9 m and 0.2 m, respectively. The cavity inside was lined with a stainless steel sheet due to better resistance to corrosion, especially from the salinity of the feed water. The absorber plate (of thickness 0.04 m), which was made of galvanised steel and painted matt black (to increase absorptivity), was welded to the inside of the frame. The wood exterior of the system cavity insulated the absorber plate from underneath to avoid heat loss. The frame was covered with a 6 mm glass cover, which acted as the condenser chamber. The system was inclined at 24°C to the south, which corresponds to the latitude of Riyadh, which allowed the free fall of feed water film on the absorber plate and maximises the solar radiation incidence on the absorber plate surface during the duration of the experiments. The feed water was connected to a flow meter; the flow meter was used to control the intake of feed water into the system. The water passing through the flow meter went into a distribution pipe fitted with nozzles (see Fig. 3), distributed equally on the distribution pipe to create a layer of water falling film on the absorber plate. To investigate the effect of glass cover cooling on the performance of the inclined solar water distillation systems, two systems were set up and run concurrently. One was a system without glass cooling (ISWD) (see Fig. 2) and the other a system with glass cooling techniques (see Fig. 4). Two cooling

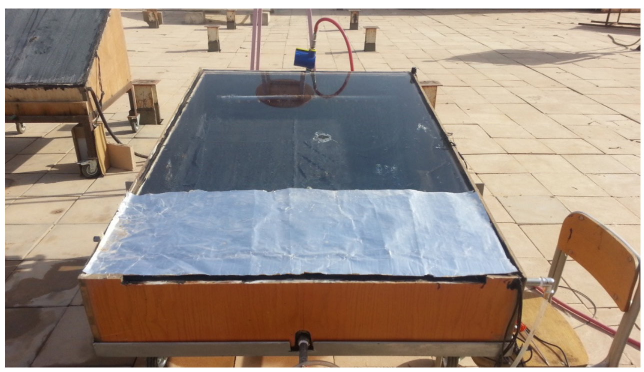

Fig. 4. A pictorial diagram of the inclined solar distillation system (glass cover shaded with silver shade mesh (SSM) (ISWD-SSM, the same system was used for ISWD-WF).

techniques were employed: a) part of the glass area shaded with Silver Shade Mesh (SSM) (ISWD-SSM), and b) the glass was cooled with intermittent water film (WF) flowing on the glass cover (ISWD-WF). The Silver Shade Mesh shading material acted as a mirror, reflecting away the sun and its heat. It was mounted on the glass cover, covering about 25% of its area with a 4 cm gap between it and the glass cover to form a kind of chimney through which a better convection occurred to keep the plate temperature lower than that of the system without the shading plate. The 4 cm gap between the shading material and the glass cover was suggested and tested by Deniz [1]. The falling film flow rate of 1.5 m/s (an optimised feed water flow rate) on the glass cover, as suggested and tested by Janarthanan et al. [91], was adopted for the experiment. The experiment was carried out between 8:00 and 18:00 for ten consecutive days during the month of June 2015 under the climatic condition of Riyadh, Saudi Arabia.

The following system properties were measured during the experiments: the ambient temperature, absorber plate temperature, glass cover temperature, air–vapour mixture temperature, feed water inlet temperature, feed water outlet temperature, feed water inlet flow rate and solar radiation. Temperature measurements were done using K-type thermocouples. The temperature data were retrieved from the K-type thermocouples using a ten –channel digital thermometer (MDSSi8 series digital, Omega) with 0.5°C accuracy. The feed water flow rate was measured with a flow meter; the solar radiation measurements were taken using the Eppley radiometer pyranometer coupled to a solar radiation meter model HHM1A digital, Omega 0.25% basic DC accuracy and a resolution of 0.5 from 0 to 2800 W/m^2. A calibrated tube was used to collect and measure the distillate output.

3. The system energy equations description and efficiency

The thermal process of an inclined solar water distillation system is shown in Fig. 1. The figure captures the heating process from the sun's energy incidences on the surface of the system through the glass (the amount of sunshine that will pass through depends on the glass transmissivity) to the absorber plate. The amount of solar energy absorbed by the absorber plate depends on its absorptivity. These energies create heat flux in the system – the radiation heat transfers from the plate to glass cover, the convection heat transfers from the plate to the water, the radiation and convection heat transfer from the glass to the atmosphere or the surroundings. These processes resulted in evaporation of the feed water and condensation of the distillate.

In the figure, T_p, T_w, T_m, T_g, T_a and $T_{w,ex}$ are the absorber plate temperature, water temperature, air–vapour mixture temperature, glass temperature, ambient temperature and the feed water exit temperature, respectively. Q_{evap}, Q_{cond}, $Q_{c,p-w}$, $Q_{r,p-g}$, $Q_{r,g-a}$ and $Q_{c,g-a}$ are evaporation heat flux, condensation heat flux, the radiation heat transfer from the plate to glass cover and the convective heat transfer from the plate to water, the radiation heat transfer from the glass to atmosphere at the temperature of "T_a" and the convection heat transfer from the glass to atmosphere at the temperature of "T_a", respectively. I, α and τ are the solar intensity, the transmissivity of the glass and the absorptivity of the absorber plate, respectively. Aybar (2006) [12] has given the energy balance of the system components as follows:

3.1. The absorber plate

$$M_p C_p \frac{dT_p}{dt} = I\tau\alpha - Q_{r,p-g} - Q_{c,p-w} \tag{1}$$

where the energy equation for the water film that flows on the absorber plate can be written as:

The feed water film on the absorber plate

$$\rho_w C_w b \frac{dT_{w,ex}}{dt} = C_w\left(\dot{m}_{in}T_{w,in} - \dot{m}_{ex}T_{w,ex}\right)\frac{1}{L} + Q_{c,p-w} - Q_{evap} \tag{2}$$

where "$T_{w,ex}$" is the exit temperature of the feed water on the absorber plate, "T_w" is the inlet temperature of feed water, and "ρ_w," "C_w," "b," and "L" are the water density, specific heat of water, water film thickness and length of cavity, respectively. The mass flow rates, "m_{in}" and "m_{ex}", are the inlet mass flow rate of water per unit width and the exit mass flow rate of feed water per unit width.

3.2. The glass cover

$$M_g C_g \frac{dT_g}{dt} = Q_{r,p-g} + Q_{cond} - Q_{r,g-a} - Q_{c,g-a} \tag{3}$$

3.3. The vapour mass

$$\frac{dM_v}{dt} = \left(\dot{m}_{evap} - \dot{m}_{cond}\right)LW \tag{4}$$

where "M_v" is the vapour mass within the cavity, and "L" and "W" are the length and the width of the cavity, respectively.

3.4. The system efficiencies

$$\eta(\%) = \frac{m_{cond}h_{fg}}{I_{eff}.A}\cdot 3600 \tag{5}$$

where η is efficiency.

4. Experimental results and discussion

The experiments were carried out between 1st and 29th of June, 2015. The solar radiations and ambient temperatures for some selected days (June 7 [Day 1 for ISWD-WF vs. ISWD], June 10 [Day 2 for ISWD-WF vs. ISWD], June 14 [Day 3 for ISWD-WF vs. ISWD], June 16 [Day 1 for ISWD-SSM vs. ISWD], June 19 [Day 2 for ISWD-SSM vs. ISWD] and June 24 [Day 3 for ISWD-SSM vs. ISWD]) between 8:00 am to 6:00 pm are as shown in Figs. 5–8. A clear day's solar energy measurements on the surface of ISWD-WF vs. ISWD, and ISWD-SSM vs. ISWD, all inclined at angle 24° to the south (which corresponds to the latitude of Riyadh) are shown in Figs. 5–6. The solar irradiation pattern in each illustration of the experiments agrees with expectation. The solar radiation, as measured, shows that Riyadh receives high solar energy, especially during the summer time. Figs. 7–8 show the ambient temperature around the systems. While there is no empirical correlation between solar irradiation and ambient temperature, it was seen that the ambient temperature rises with an increase in the solar radiation. The highest solar radiation logged during the experiment was 1017 W/

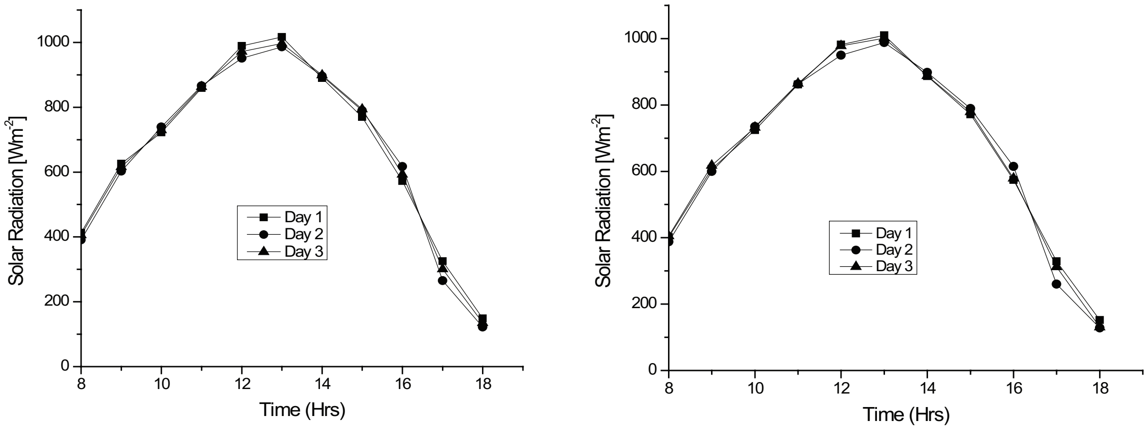

Fig. 5. Hourly variations of solar intensity vs. local time for (a) ISWD-WF, (b) ISWD.

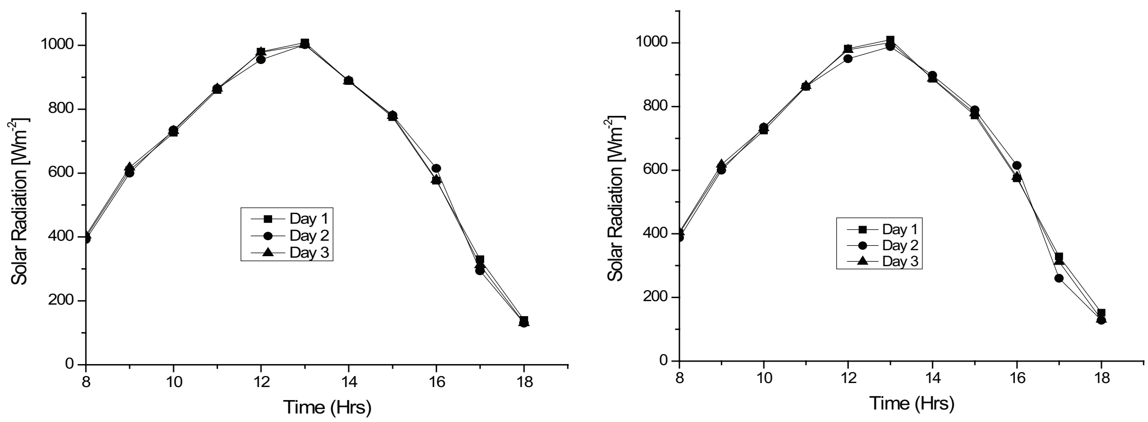

Fig. 6. Hourly variations of solar intensity vs. local time for (a) ISWD-SSM, (b) ISWD.

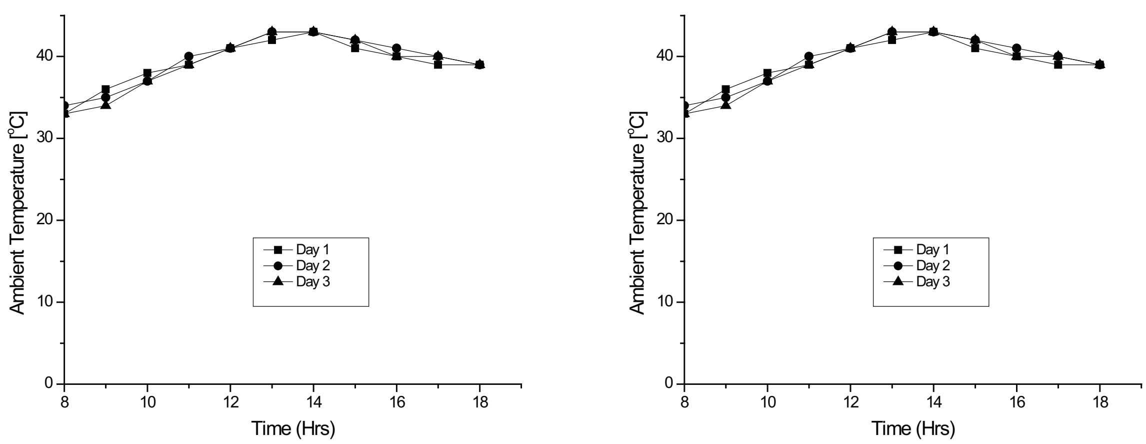

Fig. 7. Ambient temperature vs. local time of the days for (a) ISWD-WF, (b) ISWD.

m^{2,} while the maximum ambient temperature recorded was around 43°C (Figs. 5–8). The solar radiation and ambient temperature are essential for a high production of distilled water. As stated earlier, ISWD-WF and ISWD-SSM set-ups were run currently with the ISWD as a control system. It can be observed from Figs. 5–8 that the solar radiation and ambient temperature data were almost the same between the modified systems (ISWD-WF and ISWD-SSM) and the control system (ISWD). Running the systems concurrently was to ensure the systems were exposed to the same

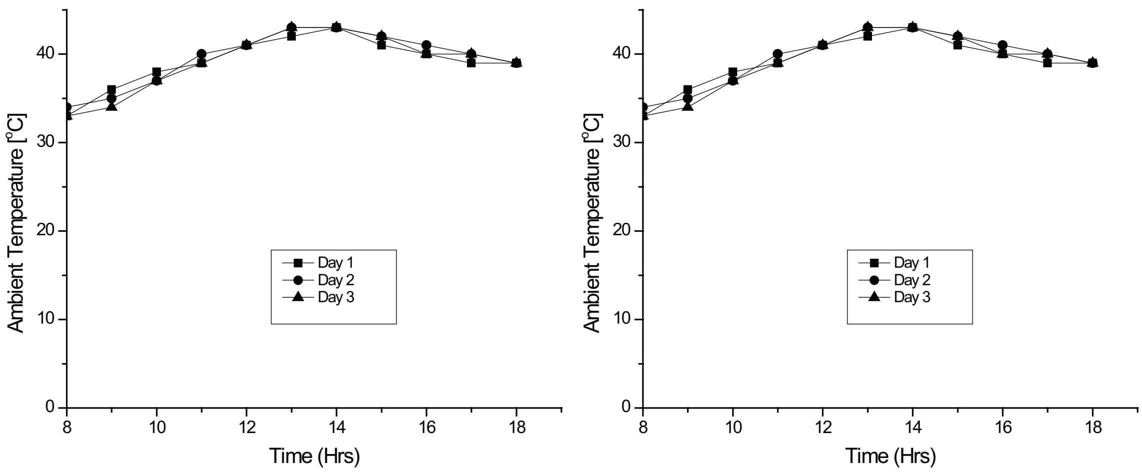

Fig. 8. Ambient temperature vs. local time of the days for (a) ISWD-SSM, (b) ISWD.

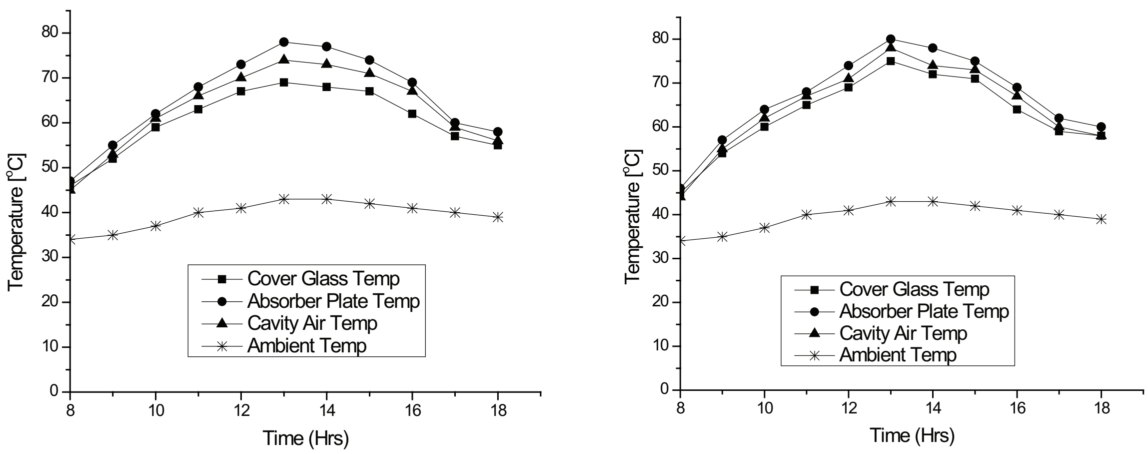

Fig. 9. Typical variation in temperature of influencing parameters in (a) ISWD-WF, (b) ISWD.

weather condition to test the effect of design modifications on the systems' performances.

The temperature distribution of ISWD-WF in comparison with ISWD is shown in Fig. 9. Fig. 9a shows the hourly temperature of the ISWD-WF components: absorber plate, the cavity, cover glass temp and the surrounding ambient temperatures. Fig. 9b shows the same for the ISWD components. In Fig. 9, the early hours of the experiments (between the hours of 8:00 am to 10:00 am) show a close temperature measurement for the absorber plate temperature, cavity air temperature and the cover glass temperature in the ISWD-WF and the ISWD. The early hour's low-temperature recordings of the absorber plate and cavity air are due to two things: (a) low temperature of the early hours feed water and (b) the time required for the absorber plate to absorb enough heat energy to raise its temperature, due to its thickness. A close temperature measurement of the system components will mean low evaporation and condensation. This justifies the low productivity of the systems in the early hours of the day. In Fig. 9a from 10:00 am the ISWD-WF shows a significant temperature difference between the cover glass temperature and the cavity air temperature, as compared to what is seen in the ISWD. The significant temperature difference can only be explained as the effect of the intermittent cooling of the cover glass with water film that resulted into higher condensation. The effect of the intermittent water film cooling can be easily observed from the comparison of Fig. 9a and 9b; the temperature difference, in particular between the cover glass and the cavity air, widens with an increase in hourly solar radiation and ambient temperature. The higher the temperature difference between the cover glass and the cavity air, the more the condensation. The contrary is observed in Fig. 9b, where the temperature difference between the cover glass and the absorber plate is very small. The temperature difference between the two, cavity air and cover glass, plays a major role in the hourly productivity of the systems.

The maximum temperature reached by the absorber plate and the cavity air is higher in the ISWD as compared to ISWD-WF in Fig. 9. One explanation could be that the intermittent water film (used for cooling the cover glass

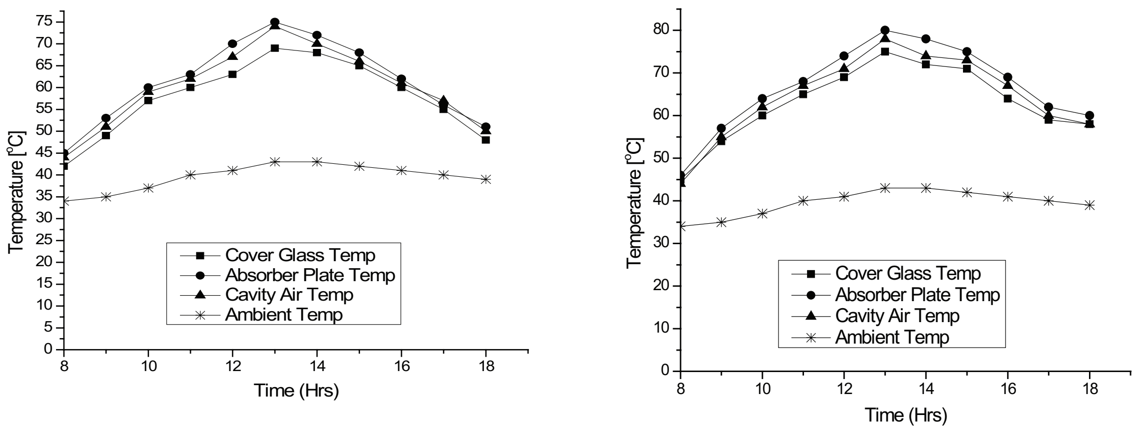

Fig. 10. Typical variations in temperature of influencing parameters in (a) ISWD-SSM, (b) ISWD.

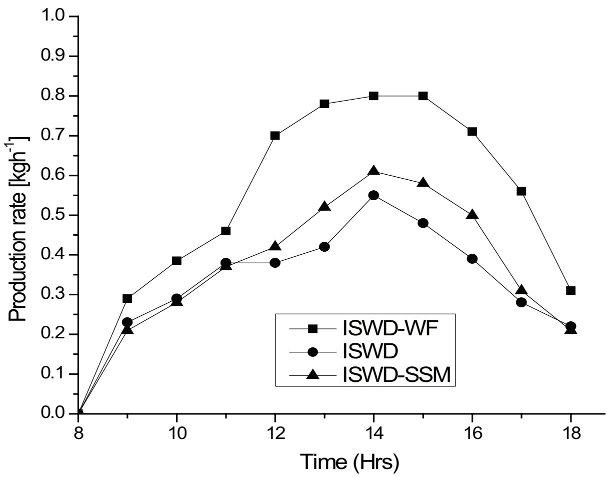

Fig. 11. Hourly production rate for the systems.

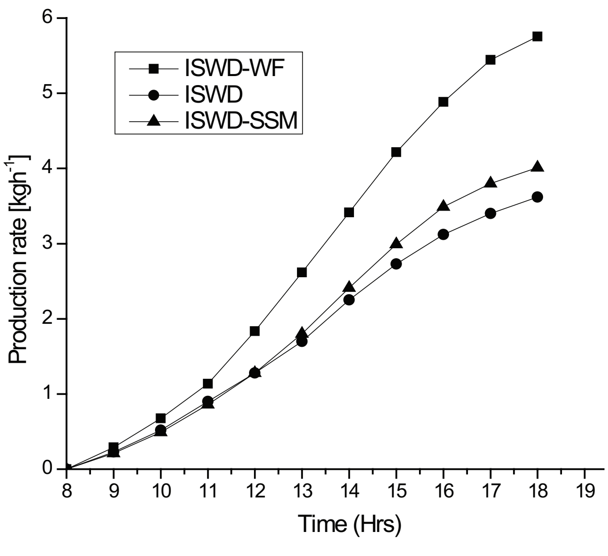

Fig. 12. Hourly cumulative productions of the systems.

in ISWD-WF) absorbed some of the solar radiation meant for the ISWD-WF absorber plate. In that case, the water film cooling does not only reduce the temperature of the cover glass but also affects the temperature of the cavity air and the absorber plate. The decrease in temperature of the absorber plate and the cavity air in the ISWD-WF due to water film cooling of the cover glass is nothing in comparison to its effect on the system performance.

The temperature distribution of ISWD-SSM in comparison with ISWD is shown in Fig. 10. The SSM cover on a quarter of the surface of the cover glass decreased the temperature of the absorber plate, cavity air and the cover glass considerably. The effect of the SSM on the cover the glass was significant between 10:00 am to 3:00 pm, as shown in the graph (Fig. 10a), where increase in the temperature difference between the cavity air and the cover glass widened as compared to the same timeline on the ISWD system (Fig. 10b). The temperature loss as a result of SSM on the cover glass is huge compared to its effect on the performance. Fig. 11 compares the production rate of the systems while Fig. 12 compares the hourly cumulative production rate for the systems. The daily production of ISWD-WF and ISWD-SSM are 5.8 kg/m^2 and 4.0 kg/m^2, respectively. The control system ISWD gives 3.6 kg/m^{2}d as the maximum daily production.

5. Conclusions

This work presents experimental results of the effect of cover glass cooling by water film and silver shade mesh on the performance of an inclined solar water distillation system. The following conclusions were drawn from the study:

- The ISWD-WF produced 5.8 kg/m^2 per day under the climatic condition of Riyadh in the month of June
- The ISWD-SSM produced 4.0 kg/m^2 per day under the climatic condition of Riyadh in the month of June
- The ISWD produced 3.6 kg/m^2 per day under the climatic condition of Riyadh in the month of June

The results show cover glass cooling influences the daily production of inclined solar water distillation significantly, especially the water film cooling. The daily performance of ISWD improved by 10.77% when the SSM was used for cover glass cooling, while the ISWD performance improved by 58.98% by using WF on the cover glass.

Acknowledgement

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Symbols

ISWD — Inclined solar water distillation
SSM — Silver shade mesh
WF — Water film
T_p — The temperature of the absorber (K)
T_g — Temperature of the glass (K)
I — Solar intensity
α — Glass cover transmissivity
τ — Absorber plate absorptivity
T_w — The water temperature (K)
T_m — The air-vapour mixture temperature (K)
T_p — The absorber plate temperature (K)
T_a — Ambient temperature (K)
T_g — The cover glass temperature (K)
$T_{w,ex}$ — The exit temperature of water on the absorber plate (K)
$T_{w,in}$ — The inlet temperature of feed water (K)
M_p — The mass of absorbing plate per square meter (kg/m^2)
C_p — The specific heat of absorbing plate material (J/kg K)
b — Water film thickness (m)
C_w — Specific heat of water (J/kg K)
C_g — The specific heat of glass material (J/kgK)
h_{fg} — The latent heat of vaporization (J/kg)
$h_{r,p-g}$ — The radiation heat transfer coefficient (W/m^2 °C)
$h_{r,g-a}$ — The radiation heat transfer coefficient from the atmosphere to glass cover (W/m^2 °C)
I_{eff} — Effective solar radiation intensity (W/m^2)
L — The length of cavity (m)
W — The width of cavity (m)
$m_{\_cond}$ — The condensation mass flow rate (kg/m^2 h)
$m_{\_evap}$ — The evaporation mass flow rate (kg/m^2 h)
$m_{\_ex}$ — The exit mass flow rate of feed water per unit width (kg/h)
$m_{\_in\,t}$ — The inlet mass flow rate of water per unit width(kg/h)
M_g — Mass of glass cover (kg/m^2)
M_v — Vapor mass within the cavity
Q_{cond} — The condensation heat flux (W)
Q_{evap} — The evaporation heat flux (W)
$Q_{c,g-a}$ — The convection heat transfer from the glass to atmosphere at the temperature of "Ta" (W)
$Q_{r,g-a}$ — The radiation heat transfer from the glass to atmosphere at the temperature of "Ta" (W)
$Q_{r,p-g}$ — The radiation heat transfer from the plate to glass cover (W)
$Q_{c,p-w}$ — The convective heat transfer from the plate to water (W)

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