An-Najah National University

Faculty of Graduate Studies

Modeling of Solar Still Enhanced with Evacuated Tube Collectors for Brine Volume Reduction from Reverse Osmosis Plants

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الإهداء

بسم االله الرحمن الرحيم

(قل اعملوا فسيرى االله عملكم ورسوله والمؤمنون) صدق االله العظيم

إلهي لا يطيب الليل إلا بشكرك ولا يطيب النهار إلى بطاعتك .. ولاتطيب اللحظات إلا بذكرك .. ولا تطيب الآخرة إلا بعفوك .. ولا تطيب الجنة إلا برؤيتك .... "االله جل جلاله ".

إلى من بلغ الرسالة وأدى الأمانة .. ونصح الأمة .. إلى نبي الرحمة ونور العالمين "سيدنا محمد صلى االله عليه وسلم ".

الى الروح التي سكنت روحي ... الى شريك الدمعة قبل الابتسامة ... الى النور الذي أمدني بالأمل في نهاية النفق ... الى الصديق و الرفيق ... الى شريك حياتي ... ثائر

إلى من كلله االله بالهيبة والوقار .. إلى من علمني العطاء بدون انتظار.. إلى من أحمل إسمه بكل افتخار .. أرجو من االله أن يمد في عمرك لترى ثماراً قد حان قطافها بعد طول انتظار وستبقى كلماتك نجوم أهتدي بها اليوم وفي الغد وإلى الأبد .. والدي العزيز.

إلى ملاكي في الحياة .. إلى معنى الحب وإلى معنى الحنان والتفاني .. إلى بسمة الحياة وسر الوجود إلى من كان دعائها سر نجاحي وحنانها بلسم جراحي ... أمي الحبيبة.

إلى من رافقتني منذ أن حملنا حقائب صغيرة ومعك سرت الدرب خطوة بخطوة وما تزال ترافقني حتى الآن.. إلى شمعة متقدة تنير ظلمة حياتي .. أختي :ميرا

إلى أخوتي ورفقاء دربي في هذه الحياة، معكم أكون أنا وبدونكم أكون مثل أي شيء، إلى من أرى التفاؤل بأعينهم والسعادة في ضحكتهم.. في نهاية مشواري أريد أن أشكركم على مواقفكم النبيلة إلى من تطلعتم لنجاحي بنظرات الأمل أخوتي: صدام، أحمد، محمد، أمير و باسل .

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الإقرار

أنا الموقعة أدناه مقدمة الرسالة التي تحمل العنوان:

Modeling of Solar Still Enhanced with Evacuated Tube Collectors for Brine Volume Reduction from Reverse Osmosis Plants

أقر بأن ما شملت عليه الرسالة هو نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، وأن هذه الرسالة ككل أو أي جزء منها لم يقدم من قبل لنيل أي درجة أو لقب علمي أو بحثي لدى أي مؤسسة علمية أو بحثية

Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degrees or qualifications.

Student's Name: **اسم الطالبة:**

Signature **التوقيع:**

Date **التاريخ:**

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Nomenclature

Symbol	Definition	Unit
A_b	Basin Area	m^2
A_{ET}	Effective area of evacuated tubes	m^2
A_g	Glass Area	m^2
A_L	Longitudinal circular area	m^2
A_s	Surface Area	m^2
A_w	Water Area	m^2
C	A constant for Nusselt number expression	
C_v	Specific heat of vapor	J/kg°C
C_w	Specific heat of water in solar still	J/kg°C
d_f	Average spacing between water and glass cover	m
F_R	Heat removal factor	-
g	Acceleration due to gravity	m/s^2
Gr	Grashof number	
h_b	Basin liner overall heat transfer coefficient	$W/m^2.°C$
h_c	Heat loss coefficient by convection from water surface for the aim of only evaporation	$W/m^2.°C$
h_{cw}	Heat loss coefficient by convection from water surface	$W/m^2.°C$
h_{ew}	Heat loss coefficient by evaporation from water surface	$W/m^2.°C$
h_{rw}	Basin water radiative heat transfer coefficient	$W/m^2.°C$
h_{tg}	Total glass heat transfer loss coefficient	$W/m^2.°C$
h_{tw}	Total water heat transfer loss coefficient	$W/m^2.°C$
h_w	Convection heat transfer coefficient from basin to water	$W/m^2.°C$
I_{eff}	Intensity of solar radiation	W/m^2
k_i	Thermal conductivity of insulation material	W/m.°C
k_v	Thermal conductivity of humid air	W/m.°C
L	Latent heat of vaporization	J/kg
l_i	Thickness of insulation material	m
L_s	Characterization length of water surface	m
M_w	Hourly output of still (condensate)	$kg/m^2.h$
M_e	Hourly evaporated output from the still (Rate of evaporation)	$kg/m^2.h$

M_b	Mass of water in basin	kg
n	Constant in Nusselt number expression	-
Nu	Nusselt Number	-
p	wet perimeter	m
Pr	Prandtl number	-
P_g	Partial Pressure at glass temperature	N/m^2
P_w	Partial Pressure at water temperature	N/m^2
q_b	Rate of total energy from the basin liner	W/m^2
q_{cg}	Rate of energy lost from glass cover by convection	W/m^2
q_{cw}	Rate of energy lost from water surface by convection	W/m^2
q_{ew}	Rate of energy lost from water surface by evaporation	W/m^2
q_{rg}	Rate of energy lost from glass cover by radiation	W/m^2
q_{rw}	Rate of energy lost from water surface by radiation	W/m^2
q_{tg}	Rate of total energy from the glass cover	W/m^2
q_{tw}	Rate of total energy from the water	W/m^2
Qu	Useful thermal energy gain from the evacuated tubes	W/m^2
q_w	Rate of total energy from the water surface	W/m^2
Ra	Rayleigh number	-
t	Time	s
T_a	Ambient temperature	°C
T_b	Temperature of basin	°C
T_g	Glass cover temperature	°C
T_v	Vapor temperature	°C
T_w	Water temperature	°C
U_{LE}	overall heat transfer coefficient from basin	$W/m^2.°C$
v	Wind Speed	m/s

Greek symbols:

μ :Viscosity of fluid (N.s/m^2)

β :Coefficient of volumetric thermal expansion (1/Temperature (K))

α_b : Basin Absorptance

α_g : Glass Absorptance

α_w : Water Absorptance

$\alpha\tau$: Absorptance – transmittance product

ρ : Density of humid air (kg/m^3)

σ : Stefan Boltzmann constant

ε_{eff} : Effective emissivity

Δ T ': Effective temperature difference (°C)

Δt: time interval (1hour).

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Abstract

In the last years and as a result of continuous increasing in world demand for potable water, shortage of fresh water became a major challenge for human society. Desalination seems to be a suitable solution for water production**.** **O~~o~~n** other hand, shortage of conventional energy needed for desalination technologies is considered as the second challenge for human society, in addition to the growing concern of brine disposal problem.

Solar still is the best alternative to convert brackish water or saline water into potable water, this technology became popular among the scientific community because of its simple working principle, its low costs and the dependence on a free and abundantly available energy. Main disadvantage of conventional still is the production rate.

This research aims at to studying the effect of coupling a single slope solar still with an evacuated tube collectors (E.T.C) through mathematical modeling. For this purpose, different models for hybrid systems were investigated, a model for a conventional still, a model for conventional still enhanced with E.T.C and model for evaporation and drying (no glass

model). For all models two different were considered, the first was considering constant parameters (properties are not function of temperature), while parameter changing with temperature are considered in the other case.

The results were obtained from solving the models numerically were analyzed and different parameters were plotted as a function of time. All obtained results showed that solar still coupled with E.T.C have as superiority over the conventional still, the potable water increased by 48% and 73% when constant and variable parameters were considered, respectively.

The effect water depth and wind speed were on water temperature, glass temperature and the output from the still were also studded. The results showed that increasing water depth decrease the fresh water productivity while increasing wind speed increases the productivity.

Removing the glass cover for brine volume reduction, showed that the evaporation rate increases by 100%.

It was concluded that the idea of using solar still enhanced with evacuated tube collectors for brine volume reduction in our study area is effective because it reduces brine volume and produces fresh water at the same time.

Chapter One
Introduction

1.1 Background

The simple substance H_2O contains two elements; hydrogen and oxygen, it is better known as water, the most important component of our lives, our bodies are two thirds water and without it, we die.

World is nearly 70% covered by water, only a very small fraction of this water is fresh water. The percentage of fresh water is almost 2.5% and only 1% of this fresh water is easily accessible [1, 2].

During the last years the consumption of water increased due to the increasing of world population, continuous industrial and technological development and differences in life styles, at the same time the available amount of water decreased dramatically which led to many problems of water such as pollution, increased salinity and running out. This continuous exhaustion of water resources leads to a water stress. Water stress refers to social, environmental and economic problems due to unmet water needs. All these factors limit water consumption per capita per day in some countries to below the 'absolute minimum' of 100 liters per capita per day (L\capita/day) recommended by the World Health Organization (WHO), for instance, the Palestinians average consumption is only 73 liter per capita per day [3, 4].

As a result, for this water crisis, finding new resources of fresh water became a great challenge to save the world and deal with fears about water problems.

The most promising technology to produce safe water is desalination; Desalination refers to the process of reducing the concentration of total dissolved solids (TDS or Salinity) in water to the recommended value (300-600 mg/L) according to WHO [5, 6].

Feed water for desalination process could be classified according to TDS into: seawater (35000 mg/L) and brackish water (3000-10000 mg/L). [6, 7]

Desalination has been used for thousands of years, started with boiling water to evaporate it away from salts by creek sailors, developed to use clay filters to trap salts by Romans [6].

Nowadays there are more than 18,983 desalination plants with working capacity exceed 95.6 million cubic meters per day [9]. All over the world, about 60% of these plants are based on membrane technologies (Reverse Osmosis) [10].

In addition, desalination feed water is come with about 59% from seawater and 21% from brackish groundwater sources, and the remaining percentage comes from surface water and saline wastewater [11].

Desalination processes could be classified using three different criteria [12].

a) What is extracted from seawater:

This group of desalination technologies could be divided into two main groups: 1) removing salts from the main stream which produce salt free latter and 2) removing water from main stream which produce salt free product as it is clarified in figure 1.1.

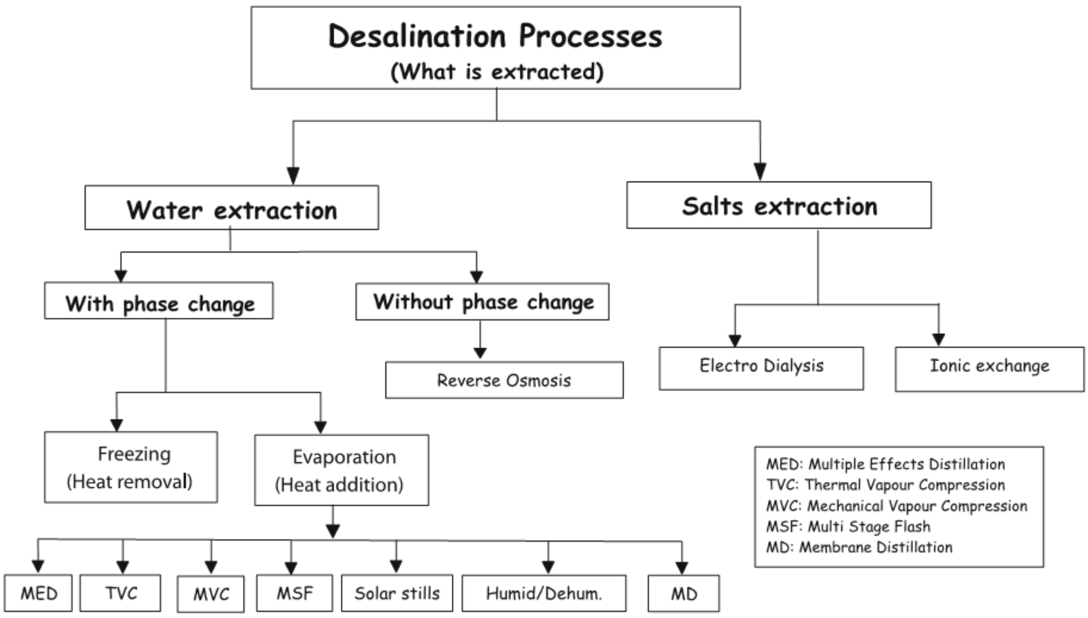

Figure 1.1: Classification of desalination technologies depending on what is extracted.

b) The separation process used:

This classification had two main groups, 1) the first group made up of thermal processes, where removing or adding heat is used to produce potable water and 2) membrane group where selective membrane is used. Figure 1.2 shows the second classification of desalination groups.

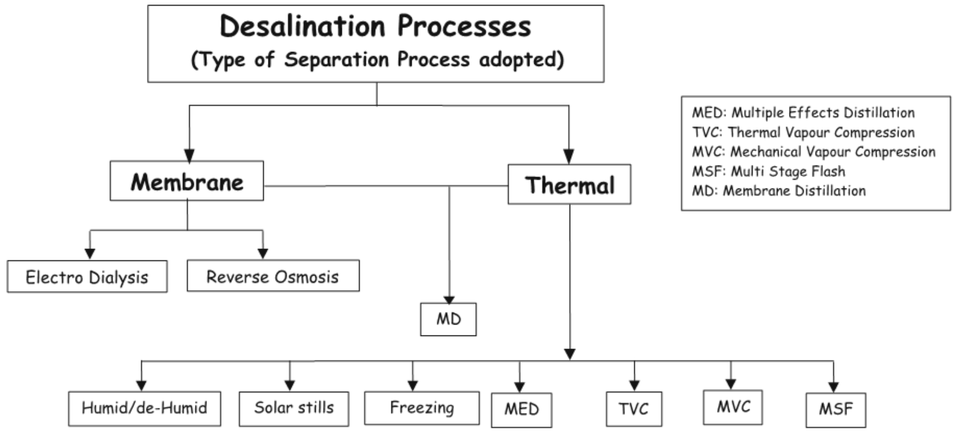

Figure 1.2: Classification of desalination technologies depending on used separation process.

c) Type of energy used:

This classification depends on type of energy used to occur the separation process as it is cleared in figure 1.3.

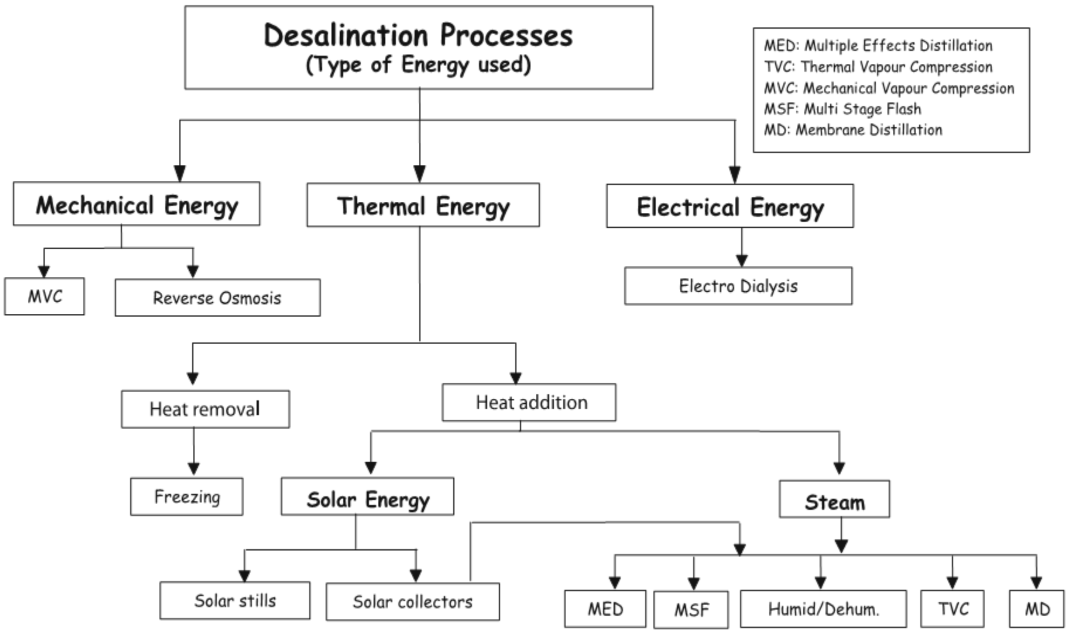

Figure 1.3: Classification of desalination technologies depending on sourced energy used.

As we mentioned earlier, about of 64% of the total desalination capacity is produced by reverse osmosis (RO) or membrane processes, so what is RO and how does it work?

Osmosis is a process by which the molecules of solvent transfer from a dilute solution (lower concentration) to a concentrated solution (higher concentration) through a semi permeable membrane. At a certain pressure called the osmotic pressure, which is needed to stop the osmotic flow, equilibrium is reached and the amount of solvent which passes in each direction is equal. When the pressure is increased above the osmotic pressure, the flow is reversed and solvent flows from the concentrate to the dilute side, this is called reverse osmosis (RO) [13].

A typical RO desalination plant consists of three stages: pretreatment, membrane and post treatment as it is illustrated in figure 1.4.

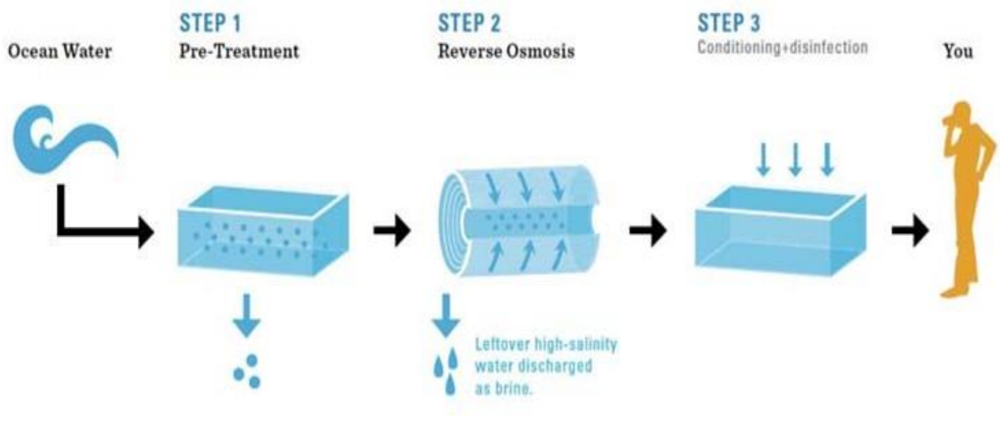

Figure 1.4: Reverse osmosis Process Stages [13].

1. Pretreatment: this section typically consists of [13, 14]:

- Screening: this process is done in order to get rid of some of the organic matter such as algae and other particulates.

- Chlorination: by adding chlorine to raw water as sodium hypochlorite or chlorine gas, this process is done to prevent fouling of the membrane (membrane contamination).

- pH adjustment: to prevent scaling (depositing of particles on membrane surface).

- Coagulants and flocculants addition: in this stage iron aluminum salts are added to the water in order to form hydroxides which help adsorbing dissolved solids and the colloidal matter agglomerate.

- Sedimentation and sand filtration: to remove the agglomerates from the feed water.

- De-chlorination: is done prior RO stage to remove residual chlorine from the feed water in order to prevent the membrane damages (poly amides) [13, 14].

2. Reverse Osmosis or Membrane Stage: this stage consists of membrane elements, pretreated saline water is passed through this stage under pressure in excess of its ‘osmotic pressure’, and a high-pressure pump coupled with energy recovery device provides this high pressure [13, 14].

3. Post Treatment: after RO stage, TDS is greatly reduced. Due to low TDS, the water can be unpalatable, corrosive and unhealthy. Post treatment section consists of lime treatment for pH correction and chlorination for disinfection as required to meet public health standards and to make the water noncorrosive to the water distribution systems [13, 14].

Seawater RO recovery rates range from 40%-60% while brackish water RO plants typically transfer 70%-85% of the feed water into permeate [15], the rest of feed water drains as retentate, concentrate or brine.

Brine discharge is the main fluid waste from a desalination plant, which contains a high percentage of salts and dissolved minerals (TDS>35000 mg/L). This stream is generally up to 40% and 90% of the intake flow rate for membrane and thermal based technologies, respectively [16].

This brine is considered as a growing concern in terms of pollution potential. This by-product is the most disadvantages of desalination plants because of its negative impact as a result of its high salinity.

Nowadays, world is seeking for eco-friendly and cheap technologies for brine disposal, brine is treated and disposed by many processes and methods as it is mentioned in table 1.1 [17].

Table 1.1: Brine disposal options.

Disposal option	Description of Technology
Surface Water Discharge	Direct disposal to surface water such as lakes and rivers
Sewer Discharge	Direct disposal to sanitary sewer system
Deep Well Injection	Brine injected into porous subsurface rock formation
Evaporation Ponds	Pond that utilizes solar energy to reduce water content in brine solution
Land Applications	Full strength or dilute brine sprayed onto land as irrigation water

Alternatively, world is trying to minimize the effluent volume from desalination plants by many options, these technologies have been developed and classified into four different categories [18]:

1. Technologies for reducing and eliminating brine disposal such as solar evaporation, phyto distillation, membrane desalination, evaporation and crystallization, two stages RO, forward RO and electrodialysis.

2. Salt recovery technologies such as SAL-PROC process, zero discharge desalination and integrated process.

3. Brine adaptation for industrial uses: such as adaptation for chlor-alkali industry and HCL and NaOH production.

4. Metal recovery technologies.

Most of the mentioned technologies either for desalination or brine treatment require energy to run plants. In the next following years, world would be looking for the most promising applications of using renewable energy in desalination plants. Sun could be the most attractive source of renewable energy, because the solar energy amount received at the ground level is free, profuse and available to all by its decentralized form.

Solar energy could be used directly to produce distillate in the solar collector, or it could be used for heat generation in order to use as a source of energy for other desalination technologies such as multi stage flash desalination (MSF) and membrane desalination (MD) [19].

Solar still is the simplest example of direct solar desalination techniques; in solar stills, a transparent cover encloses a basin of saline water, which traps solar energy within the enclosure. This energy starts to heat up the water causing evaporation, after evaporated water rises up, condensation happens on the inner face of the sloping transparent cover, this process generally produces potable water, leaving up all salts, organic, inorganic and microbes in the basin [20].

1.2 Objectives

The main objectives of this study is to determine the possibility of increasing the efficiency of the ordinary solar still desalination technology by coupling it with evacuated tube collectors and to study the possibility of using this enhanced system to minimize the brine volume produced from Reverse Osmosis plant in our study area.

The objectives are described in detail below:

1. Investigate the most used solar still technologies and evacuated tubes systems emphasizing their pros and cons.

2. Explore the most effective variables and parameters affect the ordinary solar still system and solar still-evacuated tubes hybrid system.

3. Develop a mathematical model of solar still coupled to an evacuated tubes system.

4. Determine if efficient optimal design for a solar still - evacuated tubes collectors system.

5. Investigate any possible improvements for described model.

1.3 Methodology

In order to achieve these research objectives and contribute to improving the understanding solar still-evacuated tube collectors system (SS-ETC) a theoretical, mathematical and computational work would were conducted.

Figure 1.5 summaries the flow chart and the path of the proposed study:

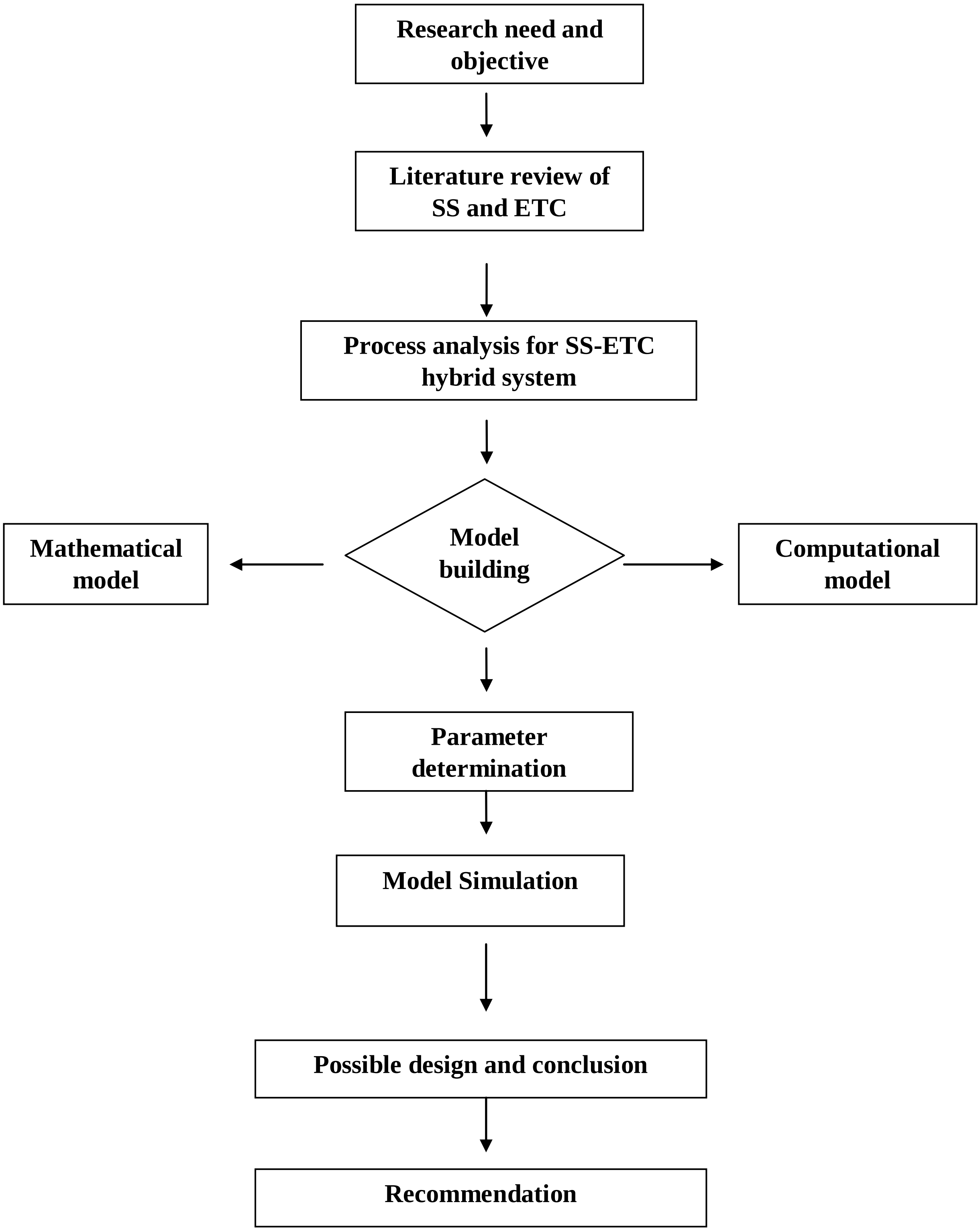

Figure 1.5: Flow chart of the proposed study.

This research work would involve the following detailed tasks:

1. Identification of solar stills and evacuated tubes collectors as thermal desalination configurations and a brief literature review about these systems. This would include there types, models and tangent parameters, and any previous enhancement were done to increase their productivity.

2. Derivation of a mathematical and computational model for the hybrid system: This model would base on mass balance; heat energy balance and heat transfer equations making assumptions where necessary and develop a steady state simulation by solving the set of these equations.

3. Evaluation of the important design and operating variables and parameters which controlling the efficiency of the system.

4. Based on the results of the previous steps, the decision will be taken if solar still – evacuated tubes system is effective for brine volume reduction or not, if not what is the alternative? This would be the last step in this research.

Chapter 2

Literature Review

Desalination has been considered as one of the earliest methods of producing drinkable water from salty water. Desalination 'like all other techniques' has been developed during last decades and with huge technologies improvement, desalination became cost competitive compared with other techniques to produce potable water [21].

Desalination process essentially separate water into two parts and whatever classification used to classify desalination technologies, energy is essential component to complete this process. Due to the continuous increasing in energy exhaustion, world started to explore any possible sustainable technology, which could be used as an alternative to produce fresh water.

Solar desalination is considered as one of the most promising technologies to produce fresh water from impure water, due to its dependency on sun one of the most important renewable energy sources.

In the literature, there are many studies about solar desalination, for example:

1. Panchal [22] has classified solar stills into active and passive systems; active systems require some mechanical source in the form of collector with solar energy, and on the other hand passive systems depend on solar radiation to evaporate water. He conducted several experiments to determine the output from double basin solar still after coupling it with

vacuum tubes, he found that the performance increased by 56% and determined the effect of coupling his system with vacuum tubes but with using black granite gravel, in this case the output has increased by 65% compared to the ordinary system without enhancement.

2. Aybar [23] determined the most important parameters for modeling solar still for desalination purpose which are convection heat transfer coefficient, heat losses, evaporation rate and condensation rate.

3. Abu-Hijleh and Mousa [24] studied the cooling effect of the glass cover on the efficiency of a single basin still and developed the numerical modeling of this system, which showed a proper increasing of the still efficiency by up to 20% when they considered the film-cooling parameter in their calculations.

4. Panchal and Patel [25] have evaluated the performance of different design, operational and climatic parameters that affect the solar still performance for desalination purposes. They have discovered that coupling the solar still with vacuum tubes will give a higher yield.

5. Shukla et al. [26] have developed an experimental investigation, mathematical analysis and economic analysis for using horizontal and vertical mesh to improve the performance of solar still desalination, they compared the results and found that the iron galvanized (GI) basin solar still with vertical mesh gives a higher output and can be helpful in obtaining pure drinking both cheaply and effectively.

6. Malaeb et al. [27] Have introduced a modified solar still design with black finished, light weight and slow rotating drum. They experimentally studied three different cover geometries of the modified still (double-sloped (triangular), single-sloped and curved cover) and the effect of cover design on the performance of the still in terms of measured temperatures and productivity.

Moreover, there are many researchers have been conducted to improve the performance of solar stills by coupling or integrating them with other techniques:

1. Fath and Ghazy [28] presented a numerical study for a hybrid system consists of a solar still coupled to a humidification-dehumidification system in order to study the influence of different environmental, operational parameters and design on productivity of the desalination system. Their results indicated that the relation between the productivity of the system and the solar intensity and ambient temperature is proportional relation, at the same time it is an inverse relation with wind velocity. However, the results have surprised them when they recognized that the dehumidifier effectiveness has an insignificant influence on the productivity.

2. Shafii et al. [29] Have investigated an experiment to equip solar still with thermoelectric modules to convert vapor latent heat to electrical energy to operate a small propeller fan for inducing forced convection inside the still. The results indicated that, by generating a forced convection, the maximum values of hourly efficiency and water yield

increased by 68% and 1.1 $kg/m^2.h$ respectively. They have used the evacuated tubes as a sun - shine collector and tried to investigate the effect of two different depths for the water inside the evacuated tubes, they observed that by filling the evacuated tubes the productivity increased by 27% compared with the half-full case.

3. Panchal et al. [30] have achieved a 35% increasing in productivity by coupling a flat plate collector with a passive solar still. They have also mentioned that the lower water depth in the still increases the output.

4. Karuppusamy [31] tried to couple an evacuated tube directly to the lower sides of a single slope solar still and explored its performance, and modified solar still productivity by using black stones; he found that the production has increased by 50% and 59% respectively. Also, he did an economic analysis and found that the payback period of his experimental setup was 235 days.

5. Belhadj et al. [32] coupled two devices which are; a conventional single slope solar distiller and a solar still with capillary film (SSCF). They presented a digital code which made it possible to obtain the values of the temperatures and the rate of condensation of this device.

6. Tiris et al. [33] made an enhancement of a solar still by coupling it with a flat plate to form a naturally circulating closed loop. This system daily production was 5 $L/m^2.day$ compared with 2.6 $L/m^2.day$ produced with solar still without any enhancement which means an average increase of 100% in yield.

7. Rai and Tiwari [34] have worked on active solar still and coupled it with a flat plate collector. They have achieved a 24% increasing in yield water compared with regular solar still. They noticed that the daily distillate output per unit area in both stills (with and without collectors) increases with increasing insulation thickness up to 4 cm rapidly and asymptotically afterwards.

We could say that desalination plants constitute a main part of the solution for continuous pressure on the existing water resources, at the same time. They - and as any other industrial activity - have the potential to cause environmental impacts on the surrounding. [35]

Brine discharge could be the main by-product produced by desalination plants, brine is the fluid waste from these plants, and it has a high concentration of salts and dissolved minerals [35].

During the last years researchers tried to modify the best eco-friendly solution for brine discharge:

1. Buckely et al. [36] in their research described multi options to decrease the amount of dissolved solids in brine discharge. These options include chemical and engineering changes within the process.

2. Ahmed et al. [37] studied the brine disposal from RO plants in Oman and United Arab Nation and concluded that well-constructed evaporation ponds would be the most appropriate brine disposal option for inland

desalination plants in Oman, while for United Arab Nation desalination plants disposal to the sea would likely to continue for foreseeable future.

3. Arino et al. [38] started to try a new promising alternative to brine disposal. They tried to reuse the brine as a salt resource, as a try to minimize its pollution. They suggested recovering valuable components contained in the brine for profitable use. As they concluded that the dual-purpose desalination and salt production plant will be a promising strategy for both reducing the total cost of pure water production and rejected brine handling in a desalination plant.

4. Munk [39] provided an ecological and economic analysis of seawater desalination plants. He focused on the problem of brine discharge in the sea. His work explained that multi stage flash (MSF) and reverse osmosis (RO) effluents are critical to marine life, due to the high concentration of copper in MSF effluent, the high salinity and the high temperature of RO effluents.

5. Morillo et al. [18] investigated four different options of brine-treatment which were: brine adaptation, salt recovery, brine reduction and adaption, brine disposal and metal recovery. They summarized the most important characteristics of these technologies by emphasizing all advantages and disadvantages, feasibility, and development stage for all options they discussed.

6. Balasubramanian [40] investigated the common brine treatment and disposal methods, he compared available options for brine disposal (Direct surface water discharge, mixing with the cooling water or sewage treatment effluents before surface discharge, deep well disposal, discharge to a sewage treatment plant, evaporation ponds, brine concentrators and land application) and concluded that these options may deem infeasible due to the following reasons: The lack of perennial stream flow with sufficient carrying capacity to assimilate the contaminants present in the concentrate, the discharge limitations in surface water bodies and the geological conditions of the area.

Chapter Three
Mathematical Modeling

3.1 Solar Stills (S.S)

Solar stills is the simplest technology which uses solar energy as a fuel for desalinating impure water like brackish or saline water. It is a simple device to get potable distilled water from impure water [21].

In conventional ordinary solar still, solar radiation falls on the glass cover, a particular part of these radiations is reflected, the cover absorbs other part and the rest of radiations enter the system through the glass cover as it is illustrated in figure 3.1 [41].

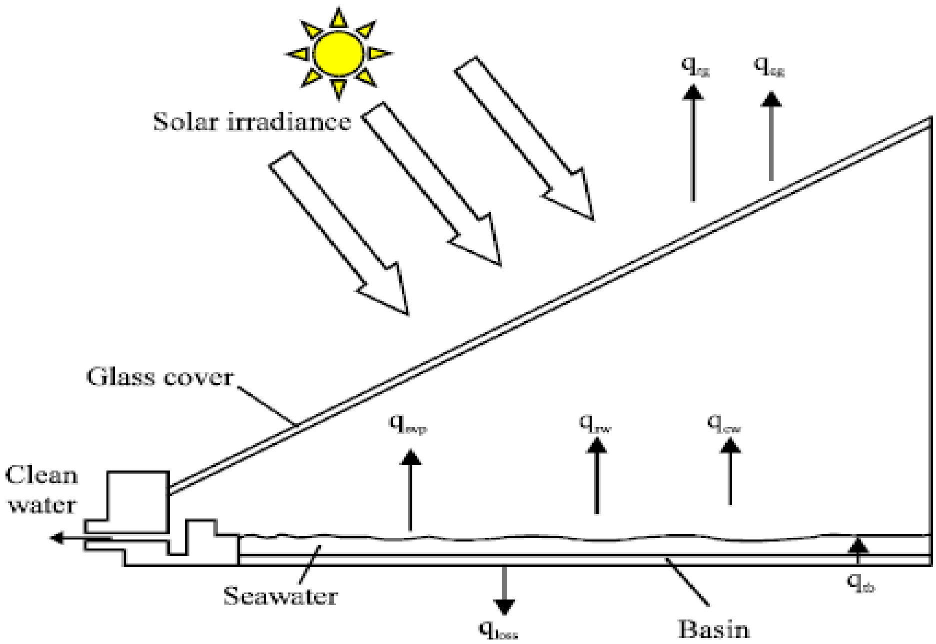

Figure 3.1: Conventional solar still [41].

The water layer and the basin receive the passed solar energy. Thus, the water layer and basin temperatures start to elevate, and energy starts to transfer between them due to the temperature difference.

The absorbance of the basin is higher than the water's, so it will be heated faster. Heat starts to conduct from its bottom surface into the water and the temperature of the water starts to increase until vaporization takes place at the interface. The surface of water, which evaporates through the confined air between the glass and water surface, makes this air saturated with moisture. Thus, this saturated air transports by:

a) Diffusion due to the partial pressure difference.

b) Convection due to the natural convection of the humid air from the water surface to the upper layer till the glass cover.

When the humid saturated air reaches the inside surface of the glass cover it starts to condensate, because the temperature of this surface (Tg) is lower than the vapor temperature, heat of condensation heats up the glass cover, the glass cover starts to exchange heat with the surrounding by radiation and convection.

The condensate flows down, collected along the glass cover and then in a channel at the end of the glass cover. Finally, it is collected in a storage tank outside of the still.

The enhanced S.S with evacuated tube collectors has the same principle of the conventional S.S. But there is a slightly difference in the heat transferred into the water layer, the enhanced still has another receiver for solar energy - the surface of evacuated tubes - this surface will absorb a part of this energy, passed it to the inner surface and convect more energy into the water as it is illustrated in Figure 3.2 [42].

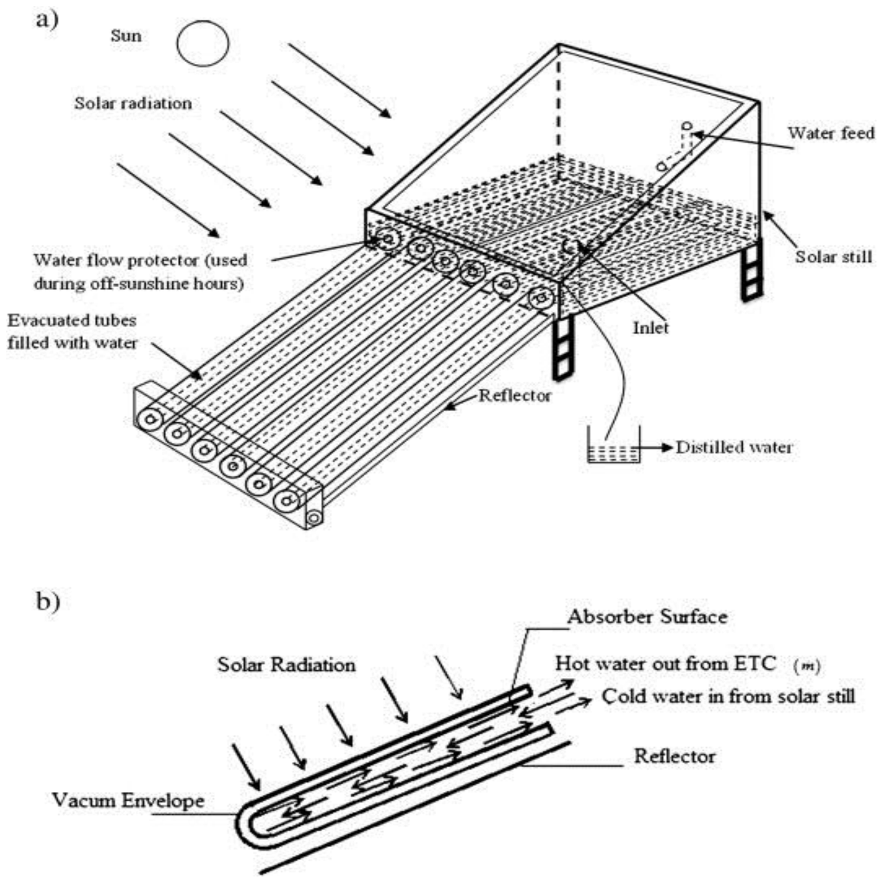

Figure 3.2: Enhanced solar still with evacuated tube collectors [42].

The performance of a solar still is generally expressed as the amount or the quantity of water condensate by unit area of the basin in one day, i.e. cubic meters, kilograms or liters of water per square meter of the basin area per day. This performance of a solar still can be predicted by solving and applying the energy and mass balance equations on the still components.

3.2 Modeling of Simple Single Slope Solar Still

Modeling is the process of producing a model. A model is a precise representation of the construction and behavior of a real system. It could be said that the model of any system is simpler to understand than the system itself because it can predict the effect of changes in any parameter before it occur [43].

In engineering applications, we often perform four types of models:

a) Physical models: used to describe small-scale systems or their parts.

b) Analog models: like which used to construct a mechanical devices.

c) Maps and drawing.

d) Mathematical models: this type of models uses the mathematical terms to represent the system and its behavior. Mathematical model uses equations that describe the performance of each component of the system [44, 45].

For solar stills, mathematical models have been developed and many researchers have experimented and predicted the performance of them.

Dunkle considered as the first who applied a complete heat and mass transfer correlations of single slope solar still [41].

Since then many other researchers have developed solar still models built on Dunkle’s model, such Hongfei et al who tried to develop Dunkle’s model under specified conditions as Dwivedi and Tiwari who verified that Dunkle’s model works well for solar still only with low basin water depth (0.01-0.03 m) [41].

After that many other researches were modify these models, but before applying any of these models, many components of the system should be understood well in order to create a clear vision of the whole process.

Solar still has three main components: a glass cover, a basin and saline water. Some of design considerations of these components are described below:

1. Basin material should be available in local markets, has accepted cost and has a high corrosion resistance [41].

2. Depth of the basin: a (5) cm is frequently the maximum depth used in stills. This depth ensures that there will be no dry over heated spots due to uneven basin bottom [46].

3. Insulation: The solar still has insulated basins in order to minimize the loss from the basin to the ambient [46].

In addition, and for minimizing the complicating of the research, we allowed the following hypotheses and assumptions [47]:

1. The temperature of the inner and the outer sides of the glass cover are supposed to be uniform.

2. The condensation rate on the glass cover is continuous and homogenous.

3. The basin is not completely insulated and the heat loss is from the bottom of the basin to the ambient.

4. The level of saline water in the basin is constant and has a continuous feed-in.

5. No ventilation in the still and no vapor leakage occurred.

After applying these assumptions, we could move to apply a heat balance on the still and its three components.

3.3 Heat balance equations

The first law of thermodynamics is a statement that defines a feature called energy; it also defines the mathematical expression of conservation of energy. Conservation of energy state that what goes in equal what goes out plus the accumulation or minus the losses.

For applying this statement on a single slope solar still, we should include a glass cover, saline water and basin separately:

- A Glass cover would be described as:

$$\alpha_g I_{eff} + q_{cw} + q_{rw} + q_{ew} = q_{cg} + q_{rg}$$ [48]

(3.1)

Where:

α_g: Glass Absorptance (0.05).

I_{eff}: Intensity of solar radiation.

q_{cw}: Rate of energy lost from water surface by convection.

q_{rw}: Rate of energy lost from water surface by radiation

q_{ew}: Rate of energy lost from water surface by evaporation.

q_{cg}: Rate of energy lost from glass cover by convection.

q_{rg}: Rate of energy lost from glass cover by radiation.

- For the saline water:

$$\alpha_w(1-\alpha_g)I_{eff} + q_w = M_b C_w \frac{dT_w}{dt} + q_{cw} + q_{rw} + q_{ew}$$ [48]

(3.2)

Where:

α_w: Water Absorptance (0.05).

α_g: Glass Absorptance (0.05).

I_{eff}: Intensity of solar radiation.

q_w: Rate of total energy from the water surface.

M_b: Mass of water in basin.

C_w: Specific heat of water in solar still.

q_{cw}: Rate of energy lost from water surface by convection.

q_{rw}: Rate of energy lost from water surface by radiation.

q_{ew}: Rate of energy lost from water surface by evaporation.

- And basin energy equation described as:

$$\alpha_b(1-\alpha_g)(1-\alpha_w)I_{eff} = q_w + q_b$$ [48]

(3.3)

Where:

α_b: Basin Absorptance (0.8).

α_w: Water Absorptance (0.05).

α_g: Glass Absorptance (0.05).

I_{eff}: Intensity of solar radiation.

q_w: Rate of total energy from the water surface.

q_b: Rate of total energy from the basin liner.

The area of the glass cover A_g, water A_w and the basin A_b are equal ($1m^2$), hence the energy equations becomes as a function of heat transfer coefficient and temperature difference:

- For glass:

$$\alpha_g I_{eff} + h_{tw}(T_w - T_g) = h_{tg}(T_g - T_a)$$ [48]

(3.4)

where:

α_g: Glass Absorptance (0.05).

I_{eff}: Intensity of solar radiation.

h_{tw}: Total water heat transfer loss coefficient.

T_w: Water temperature.

T_g: Glass cover temperature.

h_{tg}: Total glass heat transfer loss coefficient.

T_a: Ambient temperature.

- For water:

$$\alpha_w(1-\alpha_g)I_{eff} + h_w(T_b - T_w) = M_b C_w \frac{dT_w}{dt} + h_{tw}(T_w - T_g)$$ [48]

(3.5)

where:

α_w: Water Absorptance (0.05).

α_g: Glass Absorptance (0.05).

I_{eff}: Intensity of solar radiation.

h_w: Convection heat transfer coefficient from basin to water.

T_b: Basin temperature.

T_w: Water temperature.

M_b: Mass of water in basin.

C_w: Specific heat of water in solar still.

T_g: Glass cover temperature.

- For the basin:

$$\alpha_b(1-\alpha_g)(1-\alpha_w)I_{eff} = h_w(T_b - T_w) + h_b(T_b - T_a)$$ [48]

(3.6)

where:

α_b: Water Absorptance (0.8).

α_w: Water Absorptance (0.05).

α_g: Glass Absorptance (0.05).

I_{eff}: Intensity of solar radiation.

h_w: Convection heat transfer coefficient from basin to water.

T_b: Basin temperature.

T_w: Water temperature.

h_b: Basin liner overall heat transfer coefficient.

T_a: Ambient temperature.

3.4 How to calculate the heat transfer coefficients

- For the glass cover:

The losses from glass cover to ambient include external radiation and convection could be describe as:

$$q_{tg} = q_{rg} + q_{cg}$$ [48]

(3.7)

where:

q_{tg}: Total rate of energy lost from glass cover.

q_{rg}: Rate of energy lost from glass cover by radiation.

q_{cg}: Rate of energy lost from glass cover by convection.

In addition, it could be simplified as:

$$q_{tg} = h_{tg}(T_g - T_a)$$ [48]

(3.8)

where:

q_{tg}: Total rate of energy lost from glass cover.

h_{tg}: Total glass heat transfer loss coefficient.

T_a: Ambient temperature.

T_g: Glass cover temperature.

And h_{tg} as a function of wind speed could be simplified as:

$$h_{tg} = 5.7 + 3.8(v)$$ [48]

(3.9)

where:

h_{tg}: Total glass heat transfer loss coefficient.

v: wind speed.

- For water mass in the basin:

The total heat transferred between water and glass cover include convection, radiation and evaporation from water surface to the glass cover:

$$q_{tw} = q_{cw} + q_{rw} + q_{ew}$$ [48]

(3.10)

where:

q_{tw}: Rate of total energy from water surface to the glass cover.

q_{cw}: Rate of energy lost from water surface by convection.

q_{ew}: Rate of energy lost from water surface by evaporation.

q_{rw}: Rate of energy lost from water surface by radiation.

And as a term of heat transfer coefficients:

$$q_{tw} = h_{tw}(T_w - T_g)$$ [48]

(3.11)

where:

q_{tw}: Rate of total energy from water surface to the glass cover.

h_{tw}: Total water heat transfer loss coefficient.

T_w: Water temperature.

T_g: Glass temperature.

And:

$$h_{tw} = h_{cw} + h_{rw} + h_{ew}$$ [48]

(3.12)

where:

h_{tw}: Total water heat transfer loss coefficient.

h_{cw}: Heat loss coefficient by convection from water surface.

h_{rw}: Heat loss coefficient by radiation from water surface.

h_{ew}: Heat loss coefficient by evaporation from water surface.

And convection heat transfer coefficient could be calculated as:

$$h_{cw} = \frac{k_f}{d_f} C (GrPr)^n$$ [48]

(3.13)

where:

h_{cw}: heat loss coeffecint by convection from water surface to the glass cover.

k_f: thermal conductivity of humid air.

d_f: average spacing between water surface and glass cover.

C and n are constants, in most literature values of C and n are 0.075 and 0.33 respectively.

And:

$$Pr = \frac{\mu \, C_v}{k_f}$$ [48]

(3.14)

where:

Pr: Prandtl number.

μ: Viscosity of humid air.

c_v: Specific heat of humid air.

k_f: Thermal conductivity of humid air.

And:

$$Gr = \frac{g\beta\rho^2 {d_f}^3 (\Delta T')}{\mu^2}$$ [48]

(3.15)

Gr: Grashof number.

g: Acceleration due to gravity.

β: Coefficient of volumetric thermal expansion.

ρ: density of humid air.

d_f: Average spacing between water and glass cover.

ΔT ': effective temperature difference.

μ: Viscosity of humid air.

$$(\Delta T') = (T_w - T_g) + [\frac{(P_w - P_g)(T_w + 273)}{(268.9\times10^3 - P_w)}]$$ [49]

(3.16)

And:

$$P_w = \exp\left(25.317 - \frac{5144}{T_w}\right)$$ [49]

(3.17)

$$P_g = \exp\left(25.317 - \frac{5144}{T_g}\right)$$ [49]

(3.18)

where:

$\Delta T'$: effective temperature difference.

T_w: Water temperature.

T_g: Glass cover temperature.

P_w: Partial Pressure at T_w.

P_g: Partial Pressure at T_g.

The expressions, which were used for evaluating the temperature dependent physical properties of humid air, are given in table 3.1: [50]

Table 3.1: Expressions for evaluating the temperature dependent physical properties of humid air [50].

Symbol	Unit	Expression
Specific heat of vapor (c_v)	J/kg.°C	$999.2+0.1434T_v+1.101\times 10^{-4}T_v-6.7581\times 10^{-8}T_v{}^3$
Thermal conductivity of humid air (k_v)	W/m.°C	$0.244+0.7673\times 10^{-4}T_v$
Vapor dynamic viscosity (μ)	kg.s/m	$1.718\times 10^{-5}+4.62\times 10^{-8}T_v$
Vapor density (ρ)	kg/m^3	$\frac{353.44}{T_v+273.15}$
Coefficient of volumetric thermal expansion (β)	-	$\frac{1}{T_v+273.15}$

Where:

$$T_v = \frac{T_W + T_g}{2}$$ [50] (3.19)

In addition, for h_{rw}:

$$h_{rw} = \varepsilon_{eff}\sigma\left[\left[(T_w + 273)^2 + \left(T_g + 273\right)^2\right]\left[T_w + T_g + 546\right]\right]$$ [48]

(3.20)

Where:

h_{rw}: Heat loss coefficient by radiation from water surface to the glass cover.

σ: Stefan Boltzmann constant (5.67×10^{-8} W/m^{2}K^4) [48].

ε_{eff}: effective emissivity (0.82) [48].

Moreover, for h_{ew}:

$$h_{ew} = \frac{0.01623 h_{cw}\left(P_W - P_g\right)}{\left(T_W - T_g\right)}$$ [48]

(3.21)

where:

h_{ew}: Heat loss coefficient by evaporation from water surface to the glass cover.

h_{cw}: Heat loss coefficient by convection from water surface to the glass cover.

P_w: Partial Pressure at T_w.

P_g: Partial Pressure at T_g.

Finally, for the basin:

$$h_b = \frac{ki}{li}$$ [51]

(3.22)

Where:

k_i: The thickness of insulation material (0.004m

l_i: The thermal conductivity of insulation material polyurethane foam (PUF) is 0.024 W/m.°C [48].

3.5 Modeling of the Single Slope Solar Still Enhanced with Evacuated Tube Collectors

The evacuated tubes are directly coupled with the solar still, the water enters the tubes and back to the basin continuously, the following theoretically analysis is done for it:

$$Q_u + \alpha_w(1 - \alpha_g)I_{eff} + h_w(T_b - T_w) = M_b C_w \frac{dT_w}{dt} + h_{tw}(T_w - T_g)$$ [48]

(3.23)

$$Q_u = A_{ET} \mathrm{F}_R \left[(\alpha\tau)_e I_{effe} - U_{LE} \left[\frac{A_L}{A_{ET}} \right] (T_w - T_a) \right]$$ [48]

(3.24)

where:

Qu: Useful thermal energy gain from the evacuated tubes.

α_w: Water Absorptance.

α_g: Glass Absorptance.

I_{eff}: Intensity of solar radiation.

h_w: Convection heat transfer coefficient from basin to water.

T_b: Basin temperature.

T_w: Water temperature.

M_b: Mass of water in basin.

C_w: Specific heat of water in solar still.

h_{tw}: Total water heat transfer loss coefficient.

T_g: Glass cover temperature.

A_{ET}: effective area of the evacuated tubes (A_{ET} = diameter of absorber glass tube × total length of the tubes) and it is calculated as 0.564 m^2 [48].

$A_L = \pi A_{ET}$ and it is calculated as 1.77 m^2 [48].

F_R: The heat removal factor which is taken as 0.831 [48].

The inner and outer diameter of the evacuated tube are taken as 0.047 m and 0.058 m, respectively [48].

$(\alpha\tau)_e$: The effective absorptance – transmittance of product evacuated tube which is taken as 0.8 [48].

U_{LE}: The overall heat transfer coefficient of evacuated tubes which is taken as 2.44 W/m^2°C [48].

3.6 Theoretical Productivity of Single Slope Still

Productivity of solar still in all cases (Mw) is calculated by:

$$Mw = \frac{h_{ew}(T_w - T_g)A_w}{L} \times time \qquad [48]$$

(3.25)

At t=0, the first value of T_w , T_g and T_b is recorded, and after one hour Equations 5 and 23 rearranged in order to calculate T_w because it depends on the previous value of water, basin and glass temperature, and from the calculated value of T_w, T_b and T_g could be evaluated as followed:

without tubes:

$$T_{w\,at\,t} = \left[\frac{((1-\alpha_g)\alpha_w I_{eff\,at\,t-1} + h_w(T_b - T_w)_{at\,t-1} - h_{tw}(T_w - T_g)_{at\,t-1}) \times \Delta t)}{M_b \times c_w}\right]$$

$$+ T_{w\,at\,t-1}$$

(3.26)

where:

α_g: Glass Absorptance (0.05).

α_w: Water Absorptance (0.05).

$I_{eff\ at\ t-1}$: Intensity of solar radiation at the previous time interval.

$h_{w\ at\ t-1}$: Convection heat transfer coefficient from basin to water at the previous time interval.

$T_{b\ at\ t-1}$: Basin temperature at the previous time interval.

$T_{w\ at\ t-1}$: Water temperature at the previous time interval.

$h_{tw\ at\ t-1}$: Total heat transfer coefficient from water to the glass cover at the previous time interval.

Δt: time interval (1hour).

M_b: Mass of water in basin.

C_w: Specific heat of water in solar still.

And:

$$T_g = \frac{\alpha_g I_{eff\ at\ t-1} + h_{tw\ at\ t-1} T_{w\ at\ t} + h_{tg\ at\ t} T_{a\ at\ t}}{h_{tw\ at\ t-1} + h_{tg\ at\ t}}$$

(3.27)

α_g: Glass Absorptance (0.05).

$I_{eff\ at\ t-1}$: Intensity of solar radiation at the previous time interval.

$h_{tw\ at\ t-1}$: Total heat transfer coefficient from water to the glass cover at the previous time interval.

$T_{w\ at\ t}$: Water temperature.

h_{tg}: Total heat transfer coefficient from glass cover to the ambient.

$T_{a\ at\ t}$: ambient temperature.

$$T_b = \frac{\alpha_{-b} I_{eff\ at\ t-1} + h_{w\ at\ t} T_{w\ at\ t} + h_{b\ at\ t} T_{a\ at\ t}}{h_{w\ at\ t} + h_{b\ at\ t}}$$

(3.28)

and:

$$\alpha_{-b} = \alpha_b (1 - \alpha_g)(1 - \alpha_w)$$

(3.29)

where:

α_b: Basin Absorptance (0.8).

α_g: Glass Absorptance (0.15).

α_w: Water Absorptance (0.05).

$I_{eff\ at\ t-1}$: Intensity of solar radiation at the previous time interval.

$h_{w\ at\ t}$: Total heat transfer coefficient between basin and water.

$T_{w\ at\ t}$: Water temperature.

h_b: Basin liner overall heat transfer coefficient at t.

$T_{a\ at\ t}$: ambient temperature.

With tubes:

Equation 4.23 becomes:

$$T_{w_{at\,t}} = \left[\frac{Q_{u\ at\ t-1} + ((1-\alpha_g)\alpha_w I_{eff_{at\ t-1}} + h_w(T_b - T_w)_{at\,t-1} - h_{tw}(T_w - T_g)_{at\,t-1}) \times \Delta t)}{M_b \times c_w}\right]$$

$$+T_{w_{at\ t-1}}$$

(3.30)

where:

$Qu_{\ at\ t\text{-}1}$: Useful thermal energy gain from the evacuated tubes at the previous time interval.

α_w: Water Absorptance.

α_g: Glass Absorptance.

$I_{eff\ at\ t\text{-}1}$: Intensity of solar radiation at the previous time interval.

h_w: Convection heat transfer coefficient from basin to water at the previous time interval.

$T_{b\ at\ t\text{-}1}$: Basin temperature at the previous time interval.

$T_{w\ at\ t-1}$: Water temperature at the previous time interval.

T_g: Glass cover temperature.

$h_{tw\ at\ t-1}$: total heat transfer coefficient from water surface to the glass cover at the previous time interval.

Δt: time interval (1hour).

M_w: Mass of water in basin.

C_w: Specific heat of water in solar still.

A_{ET}: effective area of the evacuated tubes (A_{ET} = diameter of absorber glass tube × total length of the tubes) and it is calculated as 0.564 m^2 [48].

$A_L = \pi A_{ET}$ and it is calculated as 1.77 m^2 [48].

F_R: The heat removal factor which is taken as 0.831 [48].

The inner and outer diameter of the evacuated tube are taken as 0.047 m and 0.058 m, respectively [48].

$(\alpha\tau)_e$: The effective absorptance – transmittance of product evacuated tube which is taken as 0.8 [48].

U_{LE}: The overall heat transfer coefficient of evacuated tubes which is taken as 2.44 $W/m^2{}^\circ C$ [48].

And equations (3.27) and (3.28) has no changes.

All the previous equations and models are modified to calculate the performance of solar still as a function of output distillate, the following section will introduce a new design for solar still by removing the glass cover because the performance in this case is the evaporation rate whether it is condensate or not.

3.7 Solar still without the Glass Cover for the aim of only Evaporation

Without glass cover and without E.T.C with constant parameters:

Balance on water will lead to:

$$\alpha_w I_{eff} + h_w(T_b - T_w) = M_b C_w \frac{dT_w}{dt} + h_{tw}(T_w - T_a)$$

(3.31)

where:

α_w: Water Absorptance (0.05).

I_{eff}: Intensity of solar radiation.

h_w: Convection heat transfer coefficient from basin to water.

T_b: Basin temperature.

T_w: Water temperature.

M_b: Mass of water in basin.

C_w: Specific heat of water in solar still.

h_{tw}: Total water heat transfer loss coefficient form water to the ambient.

T_a: Ambient temperature.

Equations (3.26) and (3.28) become:

$$T_{w\,at\,t} = \left[\frac{\alpha_w I_{eff\,at\,t-1} + h_w (T_b - T_w)_{at\,t-1} - h_{tw}(T_w - T_a)_{at\,t-1}) \times \Delta t)}{M_b \times c_w}\right] + T_{w\,at\,t-1}$$

(3.32)

where:

α_w: Water Absorptance (0.05).

$I_{eff\ at\ t-1}$: Intensity of solar radiation at the previous time interval.

$h_{w\ at\ t-1}$: Convection heat transfer coefficient from basin to water at the previous time interval.

$T_{b\ at\ t-1}$: Basin temperature at the previous time interval.

$T_{w\ at\ t-1}$: Water temperature at the previous time interval.

$h_{tw\ at\ t-1}$: Total heat transfer coefficient from water to the ambient at the previous time interval.

Δt: time interval (1hour).

M_b: Mass of water in basin.

C_w: Specific heat of water in solar still.

and:

$$T_b = \frac{\alpha_{-b} I_{eff\,at\,t-1} + h_{w\,at\,t} T_{w\,at\,t} + h_{b\,at\,t} T_{a\,at\,t}}{h_{w\,at\,t} + h_{b\,at\,t}}$$

(3.33)

and:

$$\alpha_{-b} = \alpha_b (1 - \alpha_w)$$

(3.34)

where:

α_b: Basin Absorptance (0.8).

α_w: Water Absorptance (0.05).

$I_{eff\ at\ t-1}$: Intensity of solar radiation at the previous time interval.

$h_{w\ at\ t}$: Total heat transfer coefficient between basin and water.

$T_{w\ at\ t}$: Water temperature.

h_b: Basin liner overall heat transfer coefficient at t.

$T_{a\ at\ t}$: ambient temperature.

Without Glass Cover but with E.T.C:

$$Q_u + \alpha_w I_{eff} + h_w (T_b - T_w) = M_b C_w \frac{dT_w}{dt} + h_{tw} (T_w - T_a)$$

(3.35)

where:

Q_u: Useful thermal energy gain from the evacuated tubes.

α_w: Water Absorptance (0.05).

I_{eff}: Intensity of solar radiation.

h_w: Convection heat transfer coefficient from basin to water.

T_b: Basin temperature.

T_w: Water temperature.

M_b: Mass of water in basin.

C_w: Specific heat of water in solar still.

h_{tw}: Total water heat transfer loss coefficient form water to the ambient.

T_a: Ambient temperature.

And by solving this equation for T_w at any time we get:

$$T_{w\,at\,t} = \left[\frac{Q_{u\,at\,t-1} + \alpha_w I_{eff\,at\,t-1} + h_w (T_b - T_w)_{at\,t-1} - h_{tw}(T_w - T_a)_{at\,t-1}) \times \Delta t)}{M_b \times c_w}\right] + T_{w\,at\,t-1}$$

(3.36)

where:

Q_u: Useful thermal energy gain from the evacuated tubes.

α_w: Water Absorptance (0.05).

$I_{eff\ at\ t-1}$: Intensity of solar radiation at the previous time interval.

$h_{w\ at\ t-1}$: Convection heat transfer coefficient from basin to water at the previous time interval.

$T_{b\ at\ t-1}$: Basin temperature at the previous time interval.

$T_{w\ at\ t-1}$: Water temperature at the previous time interval.

$h_{tw\ at\ t-1}$: Total heat transfer coefficient from water to the ambient at the previous time interval.

Δt: time interval (1hour).

M_b: Mass of water in basin.

C_w: Specific heat of water in solar still.

Calculating the heat transfer coefficient in this differs, because the heat transfer between water surface and ambient. Total h_{tw} here presents the total heat transfer coefficient between water and ambient, so the heat transfer will be from open surface to the ambient as the heat transfer from horizontal hot plate: [55]

$$h_c = \frac{k_f}{L_s}[Nu] \qquad [52]$$

(3.37)

and:

$$L_s = \frac{A_s}{p}$$ [52]

(3.38)

$$Nu = 0.54\,Ra^{1/4} \text{ for } 10^7 \leq \text{Ra} \leq 10^{11} \quad \text{and} \quad pr > 0.7$$ [52]

(3.39)

$$Ra = Gr \times Pr$$ [52]

(3.40)

h_c: Convection heat transfer coefficient from water surface to the ambient.

k_f: Thermal conductivity of humid air.

L_s: Characteristic length of surface water area.

Nu: Nusselt number.

A_s: Surface area.

p: wetted parameter.

Ra: Rayleigh number.

Pr: Prandtl number.

Gr: Grashof number.

And:

$$h_{rw} = \varepsilon_{eff}\sigma\left[\frac{[T_w{}^4 - T_a{}^4]}{[T_w - T_a]}\right]$$ [52]

(3.41)

h_{rw}: Radiation heat transfer coefficient from water surface to the ambient.

σ : Stefan Boltzmann constant.

ε_{eff}: Effective emissivity.

T_w: Water temperature.

T_a: Ambient temperature.

Moreover, for h_{ew}:

$$h_{ew} = \frac{0.01623 h_{cw}(P_w - P_a)}{(T_w - T_a)}$$ [52]

(3.42)

h_{ew}: Evaporation heat transfer coefficient from water surface to the ambient.

h_{cw}: Evaporation heat transfer coefficient from water surface to the ambient.

P_w: Partial pressure at water temperature.

P_a: Partial pressure at ambient temperature.

T_w: Water temperature.

T_a: Ambient temperature.

The partial pressure in this case calculated using equation (3.17) and (3.18) but at water and ambient temperatures.

And finally; rearranging equation (3.25) will lead to:

$$Mevpaorated = \frac{h_{ew}(T_w - T_a)A_w}{L} \times time$$

(3.43)

where:

M evaporated: mass of water evaporated from the basin.

h_{ew}: Evaporation heat transfer coefficient from water surface to the ambient.

T_w: Water temperature.

T_a: Ambient temperature.

A_w : Water area.

L: latent heat of evaporation.

Chapter Four
Results and Discussion

The results in this Chapter were obtained by numerically solving the mathematical model equations that have been discussed in Chapter Three. The models were employed to determine the performance of different types and configurations of solar stills.

We assumed that the whole system is in a quasi-steady state condition so, the temperatures are assumed not to change in one hour interval of time. The resolution of Equations has allowed us to obtain results, where computation has been carried out for each component of the still at an initial time (t) and at an initial temperature (Tw) with a time step equals to one hour.

4.1 Comparison between Conventional and Enhanced Still Considering Constant Properties

Equations presented in Chapter Three depend on properties of the three components of the still, the first trial of calculations is done assuming constants properties of these components during the time intervals as it is shown in Table (4.1).

Table 4.1: Design parameters of solar still for theoretical simulation considering constants properties.

Parameter	Value	Unit	Reference
Latent heat of vaporization (L)	$2260*10^3$	J/kg	[53]
Specific heat of vapor (C_v)	1810	J/kg.°C	[54]
Thermal conductivity of humid air (k_v)	0.298	W/m.°C	[55]
Vapor dynamic viscosity (μ)	$1.2*10^{-5}$	kg.s/m	[56]
Vapor density (ρ)	0.08	kg/m^3	[57]
Acceleration of Gravity (g)	9.81	m/s^2	[51]
Expansion factor of water vapor (β)	$(3\text{-}4)*10^{-3}$	-	[58]
Heat transfer coefficient by convection from water surface (h_{cw})	1.8	W/m^2°C	[50]
Heat transfer coefficient by evaporation from water surface (h_{ew})	28.5	W/m^2°C	[50]
Heat transfer coefficient by radiation from water surface (h_{rw})	8	W/m^2°C	[50]
Heat transfer coefficient by convection from glass surface (h_{cg})	8.8	W/m^2°C	[50]
Heat transfer coefficient by radiation from glass surface (h_{rg})	7.3	W/m^2°C	[50]
Convection heat transfer coefficient from basin to water (h_w)	100	W/m^2°C	50
Basin liner overall heat transfer coefficient (h_b)	7	W/m^2°C	[50]

Equations (3.4), (3.5) and (3.6) indicate that Tw, Tg and Tb depend on the amount of solar energy received by the still (I_{eff}), Table (4.2) shows the hourly average solar radiation and the ambient temperature of typical summer day (20/7/2012). This measurement was obtained from a measuring system in Az-Zubeidat village; which is a small village with population of about 2000 people and located 45km to the north of Jericho. This village has a RO desalination station which is considered as our case study.

Table 4.2: Hourly average solar radiation and ambient temperature in Az-Zubeidat village, for the day (20/7/2012) [59].

Time of the day	I_{eff} (W/m^2)	Ta (°C)
8:00 AM	336.3	35.4
9:00 AM	509.1	36.5
10:00 AM	640.8	37.7
11:00 AM	715.6	38.8
12:00 PM	747.9	39.7
1:00 PM	712.5	40.7
2:00 PM	615.4	41.5
3:00 PM	486.2	42.1
4:00 PM	337.4	41.5
5:00 PM	172.6	39.8
6:00 PM	60.8	38.8

Table (4.2) shows the available daily data which indicates that the solar radiation increases and reaches the maximum value at the mid-day then decreases, also the ambient temperature increases and reaches the maximum values between 1 and 3 pm.

Numerical calculations are initiated assuming the temperature of the main components of the still depending on the ambient temperature and the nature of the element at t = 0. Using this known values, assumed heat transfer coefficients and climatic parameters, Tw, Tg and Tb were calculated from equations (3.27), (3.28) and (3.29), respectively for one hour as time interval.

After calculating the first hourly variation of Tw, Tg and Tb, the procedure is repeated with these new values for the next time interval. Calculations showed that the first value of temperatures should be found is Tw after first time interval, because other temperatures depend on this value, the same calculations were done for conventional and enhanced still.

It is possible to compare the solar still with the enhanced one; temperatures at different points were calculated and plotted. Figures (4.1), (4.2) and (4.3) show that the temperature of any point or location in the enhanced still is higher than it for the same point in the ordinary still. For example, at the 6^{th} hour of the day (mid of the day) where (I_{eff} = 747 W/m^2), the conventional or ordinary still components temperature (glass, water and basin) are (52.5, 56.9 and 60.9 °C) respectively, and (58.3, 65.2 and 68.6 °C) for enhanced still components, this is due to the additional energy which is provided by the evacuated tubes.

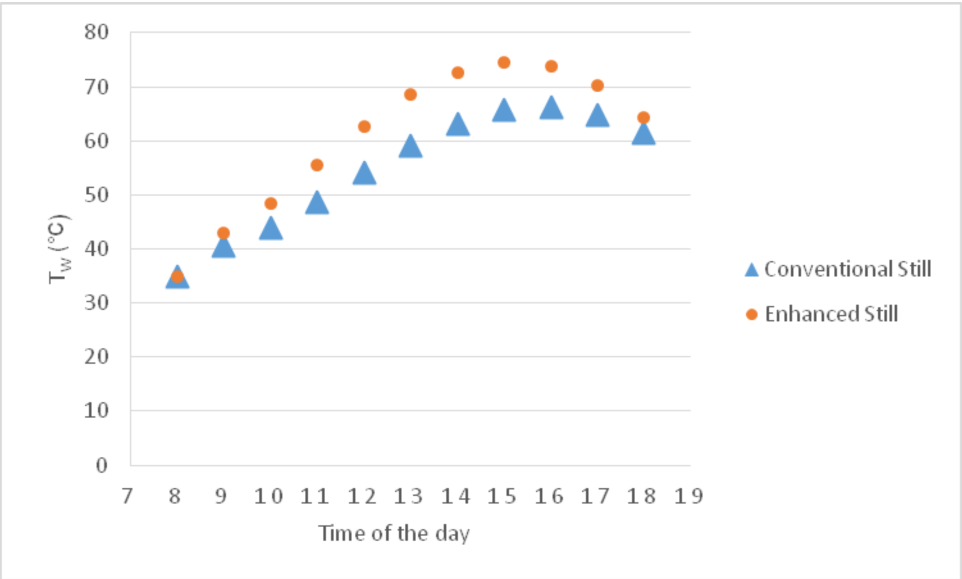

Figure 4.1: Water temperature of conventional and enhanced stills considering constant parameters.

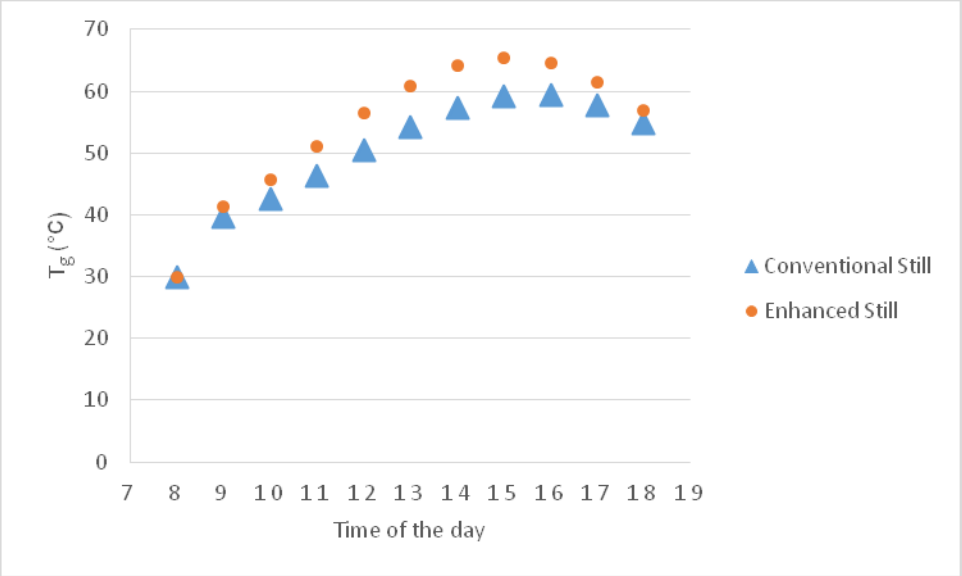

Figure 4.2: Glass temperature of conventional and enhanced stills considering constant parameters.

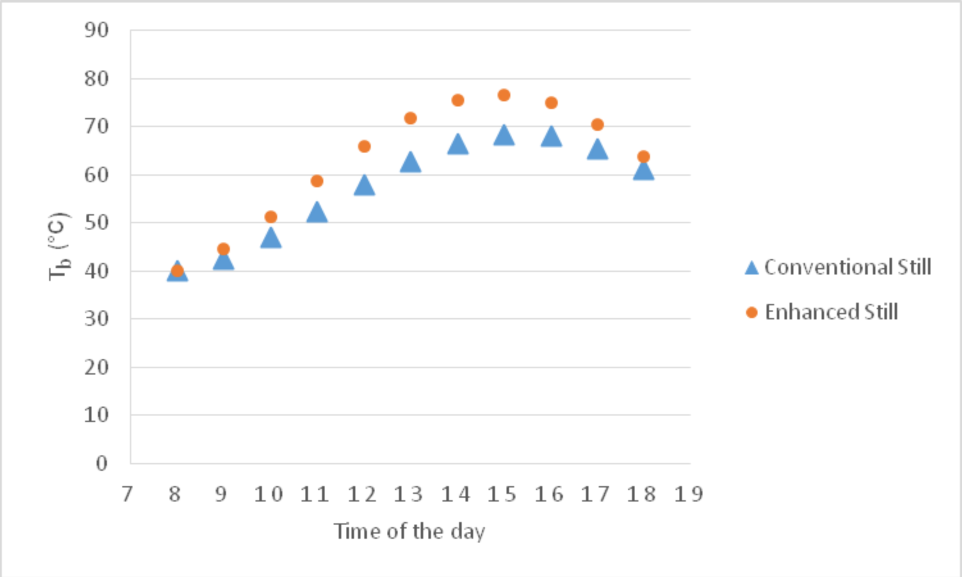

Figure 4.3: Basin temperature of conventional and enhanced stills considering constant parameters.

Figures (4.4) and (4.5) show the variation of different variables of ordinary and enhanced solar stills. It can be seen that in both case, the temperature of the basin is the maximum followed by the temperature of vapor then the temperature of water, which has been heated by the basin in a convection process due to incident rays, and the minimum temperature is the glass where the condensation occur; This temperature difference allows heat to transfer from basin to water to transfer it into vapor, also it allows vapor to move upward due to different in partial pressure, moreover, and because the vapor temperature is lower than the glass temperature it condenses and turn into water again.

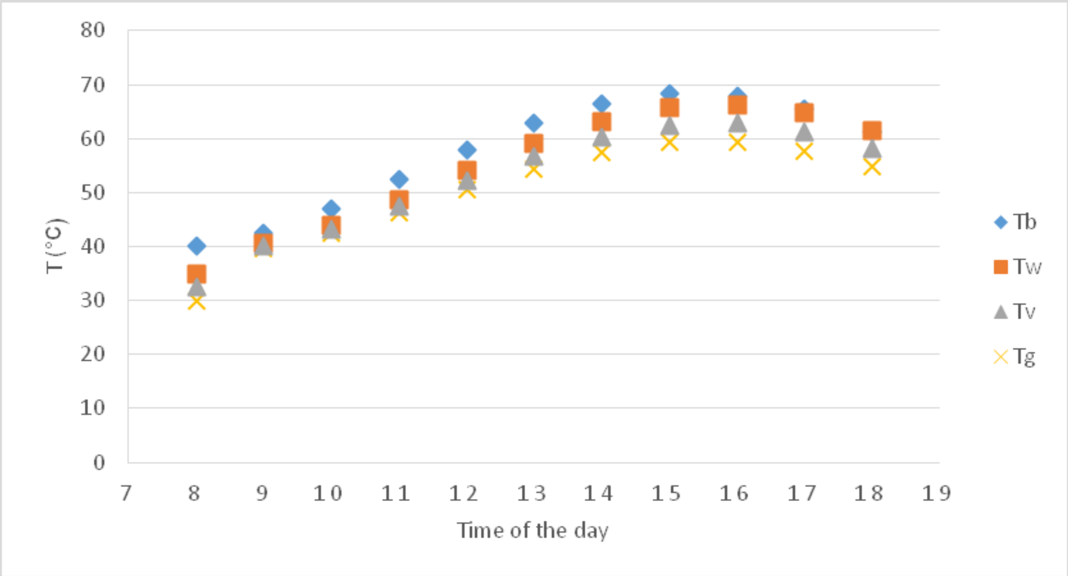

Figure 4.4: Temperatures variation between different locations on the conventional still considering constant parameters.

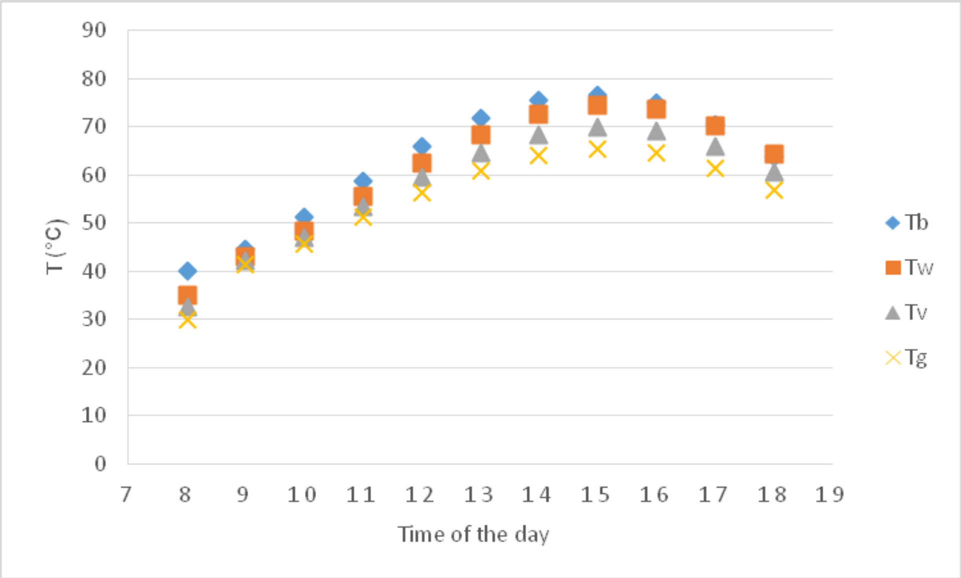

Figure 4.5: Temperatures variation between different locations on the enhanced still considering constant parameters.

After knowing Tw, Tg and Tb at any time theoretical hourly yield is calculated using Equation (3.25).

Results showed that the productivity of enhanced solar stil is higher than it for conventional still at the same conditions, which mean that the still will produce more water if it is coupled with evacuated tubes as shown in Figure (4.6).

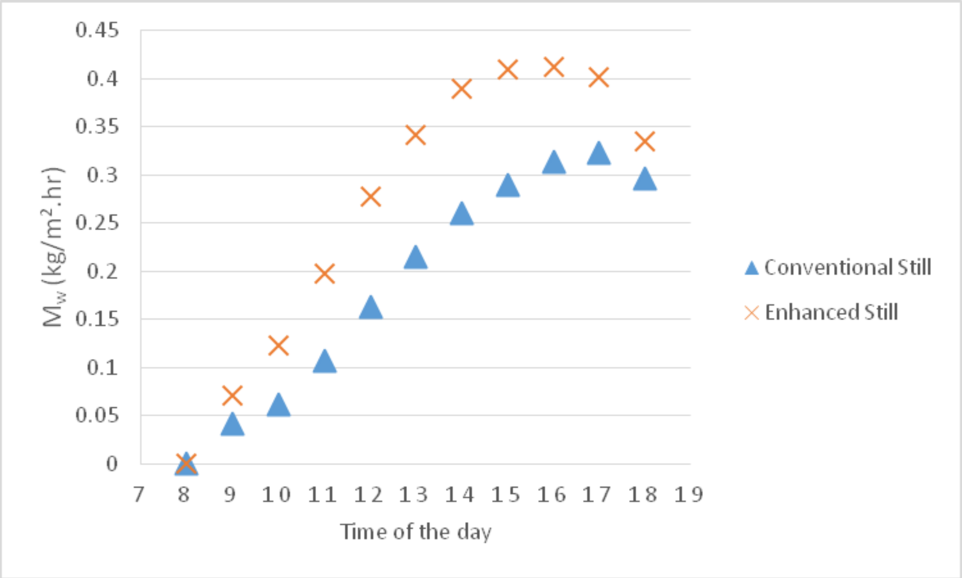

Figure 4.6: Comparison between the productivity for both still as a function of time considering constant parameters.

Calculations and results agree with karuppusamy results, he mentioned that the productivity of the conventional still is a main function of temperature difference between water in the basin and the glass cover and this agrees with our Equation (3.26) used to determine the productivity of the ordinary still. At the same time our results show that the productivity is increased by about 48%, which agrees with karuppusamy results who achieved about 50% by coupling the solar still with evacuated tube collectors in his experiment, he discussed the effect of adding the evacuated tubes on the basin which would receive additional heat energy and supply it to the water in turn to increase the temperature and it is clear in Figure (4.2) that Tw values in the enhanced still is higher than it at the same time in the conventional still and this approves karuppusamy results.

4.2 Comparison between Conventional and Enhanced Still Considering Temperature Dependent Parameters

Second trial of calculations was done using Equations from Table (3.1). These Equations depends on vapor temperature (Tv) which is calculated using Equation (3.19), the new calculated values of physical properties were used to evaluate all temperatures of the Three still components.

Figures (4.7), (4.8) and (4.9) show that even the variables are temperature dependent, the variation of the temperatures will trend in the same way. The values of temperatures of the three still components are higher than it for the conventional still.

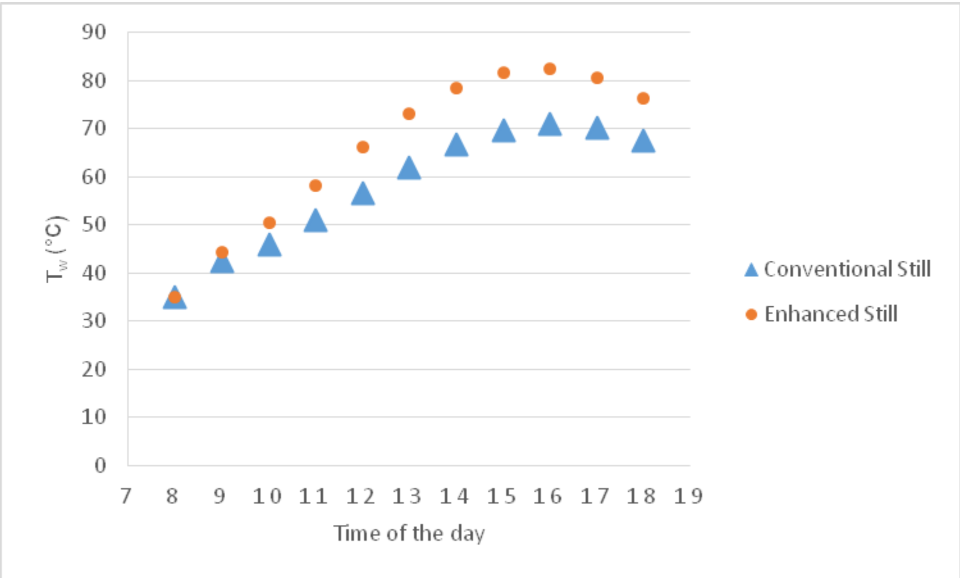

Figure 4.7: Water temperatures of conventional and enhanced stills considering variable parameters.

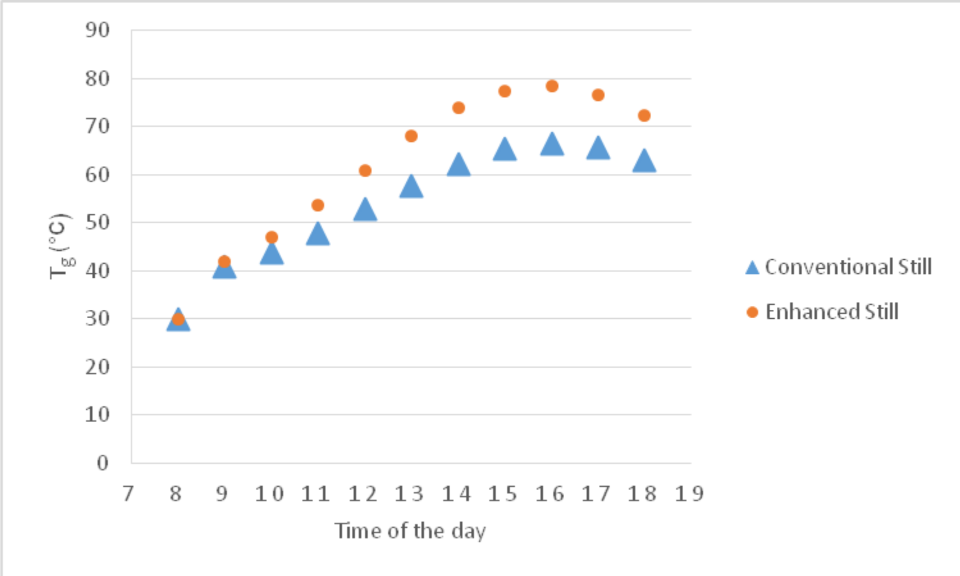

Figure 4.8: Glass temperatures of conventional and enhanced stills considering variable parameters.

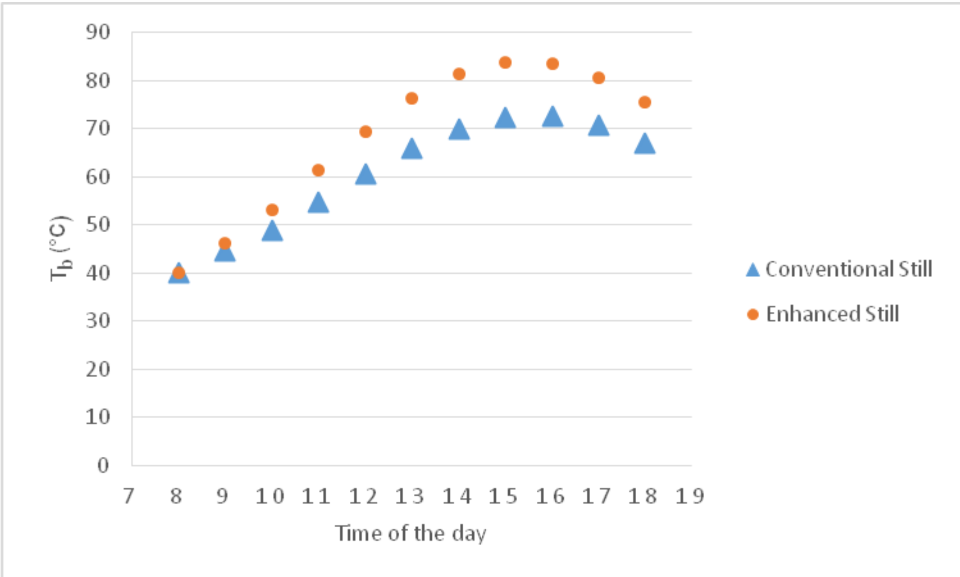

Figure 4.9: Basins temperature of conventional and enhanced stills considering variable parameters.

Figures (4.10) and (4.11) ensure that the temperature of the basin is the maximum followed by the temperature of vapor, which is in-between, the temperature of water and the temperature of glass which is the minimum again. Figure (4.12) shows the higher by 74% productivity is from the still coupled with evacuated tube collectors.

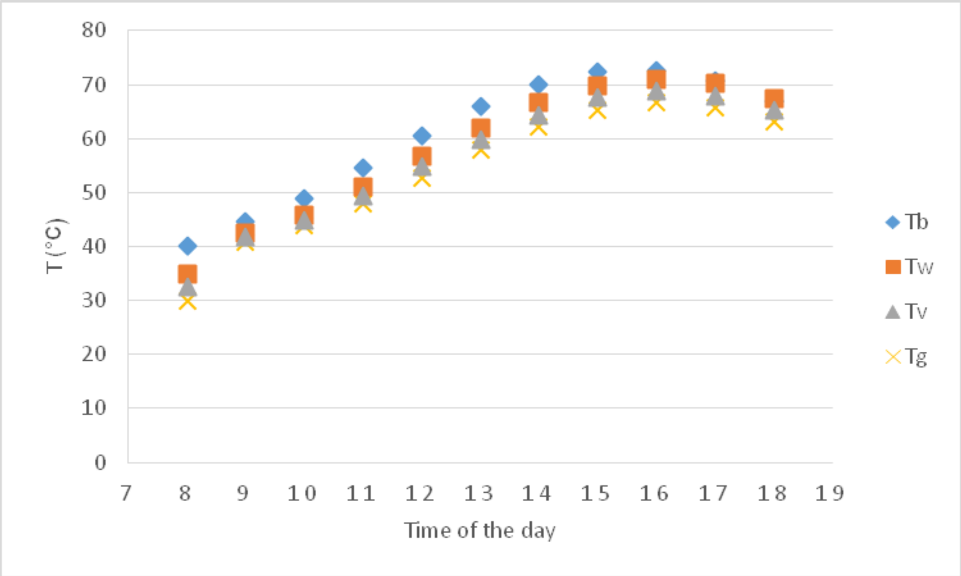

Figure 4.10: Temperatures variation between different locations on the conventional still considering variable parameters.

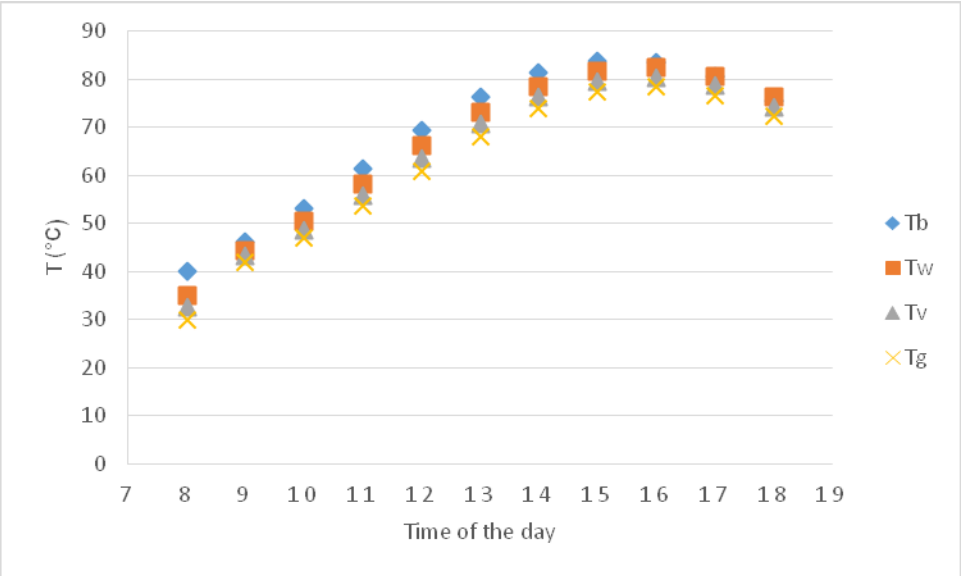

Figure 4.11: Temperatures variation between different locations on the enhanced still considering variable parameters.

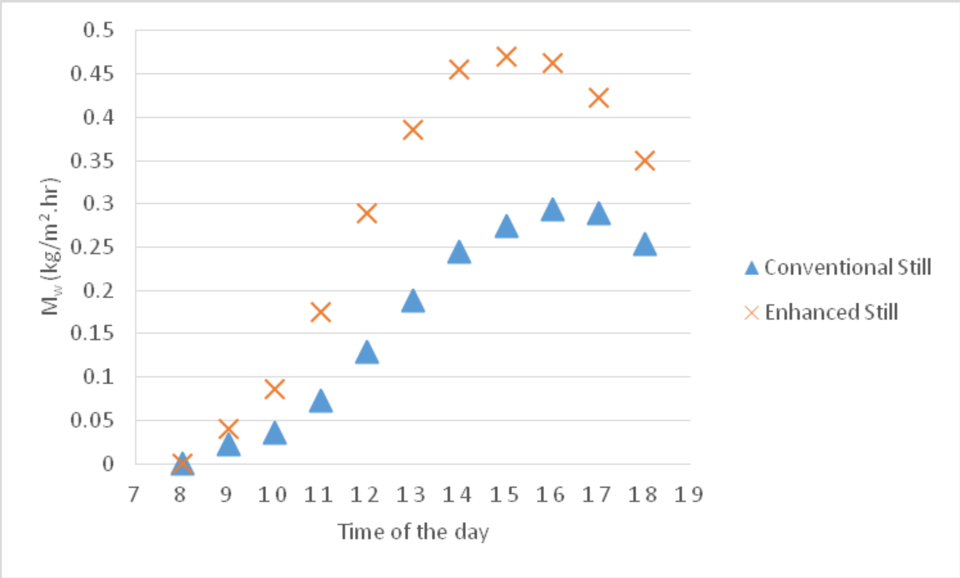

Figure 4.12: Productivity of both stills as a function of time considering variable parameters**.**

Comparing all the previous Figures data show a slightly difference between considering the parameters as constants or variables with temperature, even there are small differences in Mc values but still the enhanced still gives more output.

The performance of both studied types of solar still is affected by many parameters such as climatic parameters (solar intensity, wind speed and ambient temperature).

4.3 The Effect of Different Parameters on the Productivity of the Solar Still.

4.3.1 Wind Speed

The results of the effect of wind speed on the productivity of both types of solar still that we have studied show a different response in the previous cases. In the first case, where the physical properties were considered as constant during the day, as the wind speed changes (increase or decrease), the productivity of the still stay the same (2.1kg/m^2.day from the conventional still and 3 kg/m^2.day from the enhanced still), because the wind velocity have no effect on the performance equation so the productivity hasn't been change either for conventional or enhanced still.

Even results show that at any specific time of the day there is no change in the performance of the still due to the increase in wind velocity, they still show and confirm that the productivity of the enhanced still is higher than it from the conventional still at the same conditions.

On the other hand, the results show a different response in the second case, where the physical properties were considered as function of temperature, the productivity of the still increases as wind speed increases. Figures (4.13) and (4.14) show that with increasing the wind velocity, leads to an increasing in production of distilled water, and this is due to the increasing of heat transfer between glass cover and the ambient (h_{tg}); this lost heat considered as cooler agent of the glass, which causes a better cooling of glass cover. This will produce a higher temperature difference between water and the glass cover, and more water will condensate.

At the same time and by comparing figure (4.13) with (4.14) show that the performance of enhanced still is higher than the performance of ordinary still at the same wind velocity.

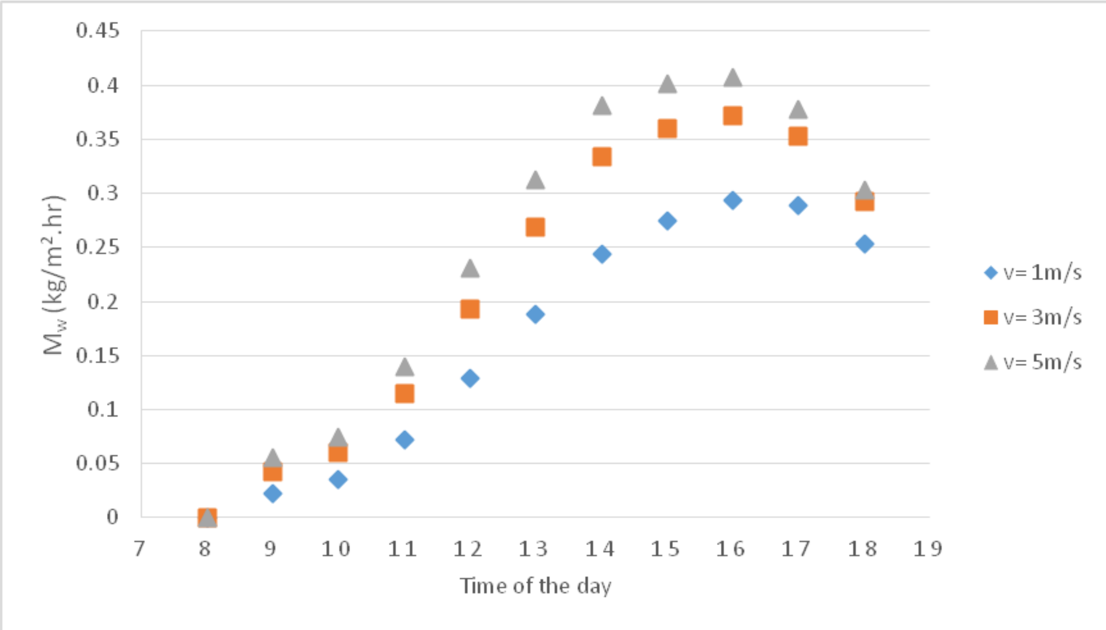

Figure 4.13: Effect of wind speed on productivity for conventional still considering variable parameters.

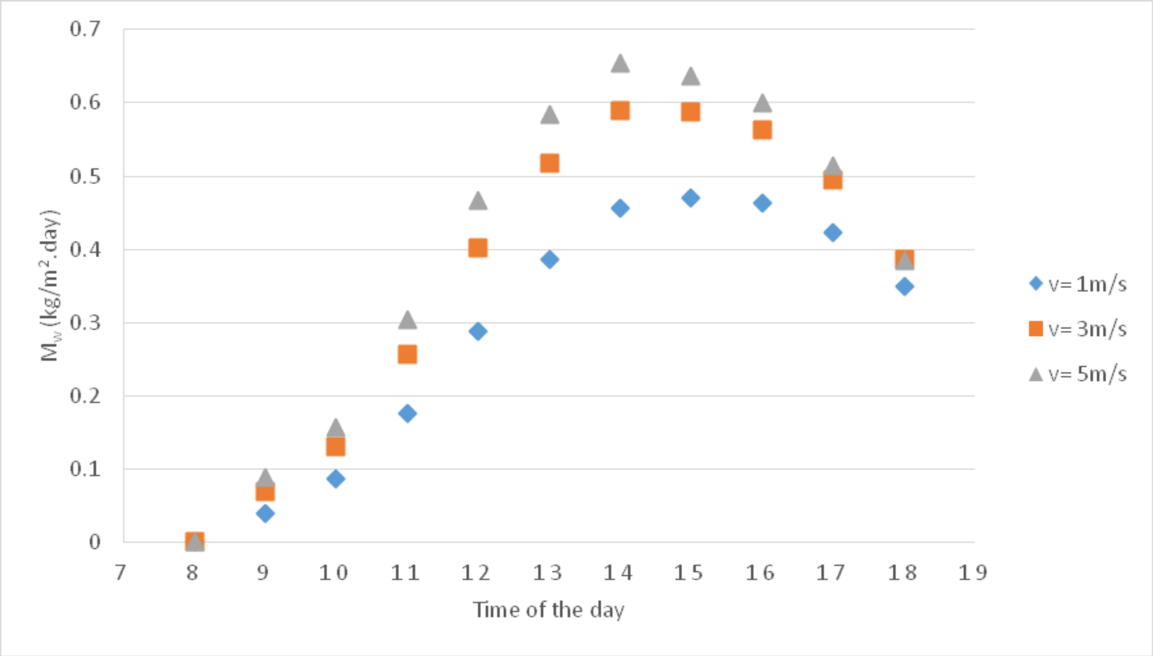

Figure 4.14: Effect of wind speed on productivity for enhanced still considering variable parameters.

4.3.2 Water Depth in the Basin

Water depth depends on the mass of the water in the basin, water depth have a significant impact on yield and efficiency of the solar still in both cases we have studied (constants and variable parameters). Figures (4.15) and (4.16) show that as the depth of the water in the basin increases the output decreases, because the evaporation rate is lower for higher depth. Hence the still with lower depth has the higher output because there is no storage effect and the heat capacity of the water in the basin is lower.

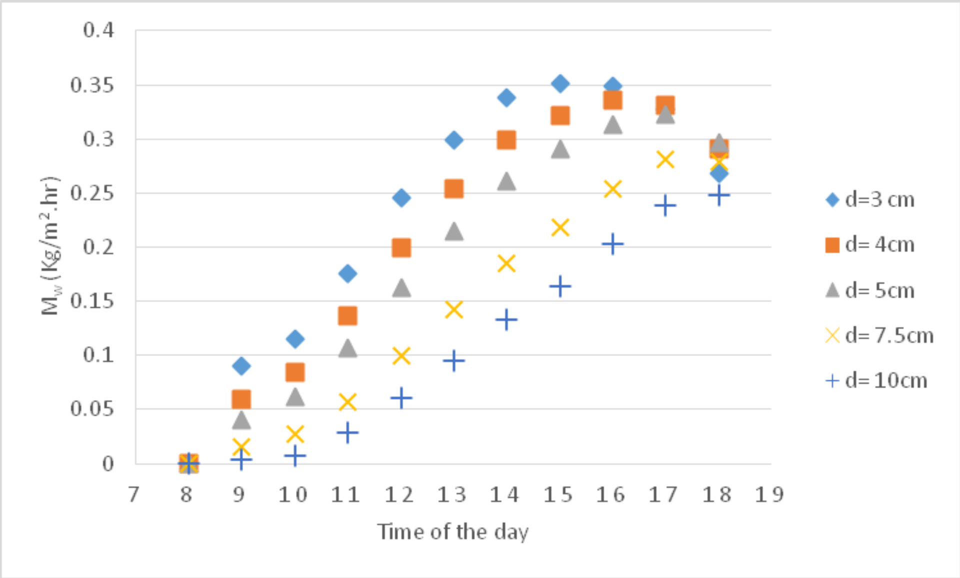

Figure 4.15: Effect of water depth on productivity for conventional still considering constant parameters.

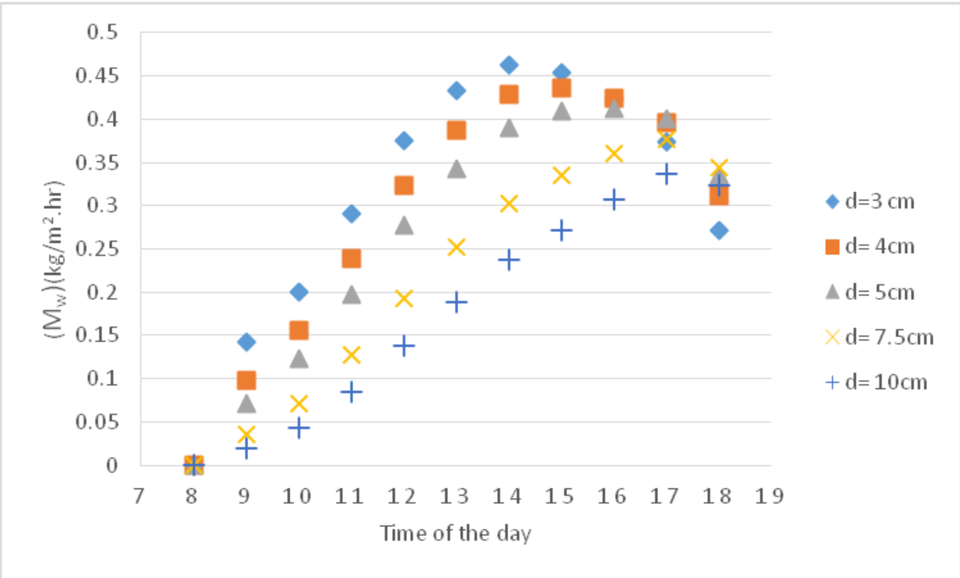

Figure 4.16: Effect of water depth on productivity for enhanced still considering constant parameters.

Figures (4.17) and (4.18) show that even when considering the properties as a temperature function, the response of the yield stays the same, and the lower depth will lead to a higher output.

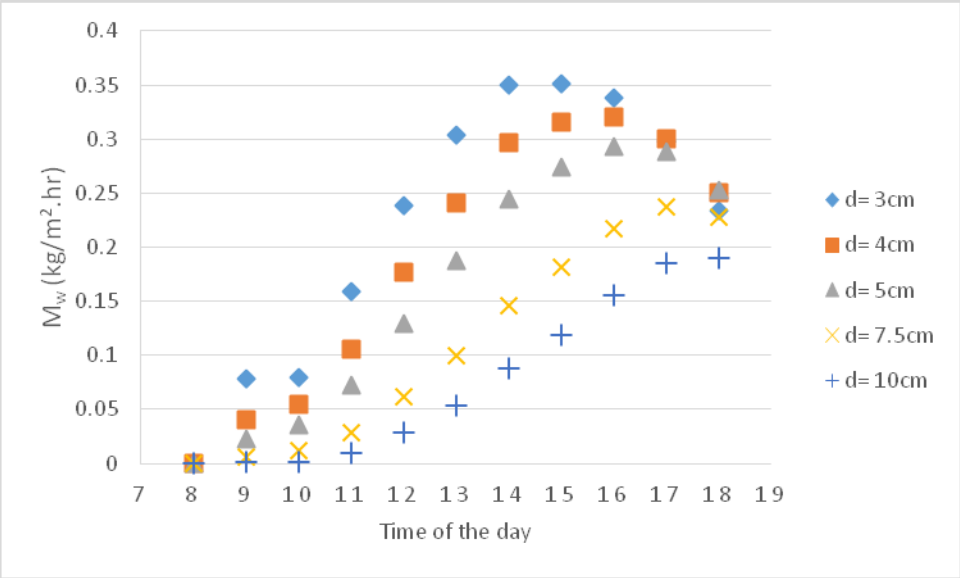

Figure 4.17: Effect of water depth on productivity for conventional still considering variable parameters.

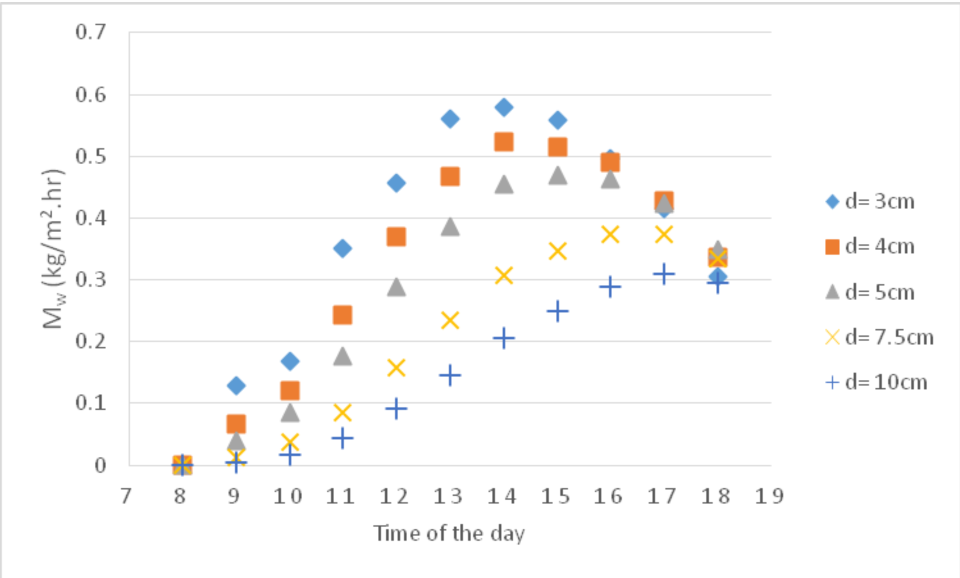

Figure 4.18: Effect of water depth on productivity for enhanced still considering variable parameters.

Again, Figures (4.13) to (4.18) show that the productivity or the output from enhanced still here are higher than the output of conventional still.

4.4 Ordinary Solar Still without a Glass Cover

The main function of previous models was the output of the still as the amount of distillated water. The objective of this section is different and the main function of re-modeling solar still is to remove the glass cover because the yield in this case is to evaporate more water whether it condensates or not.

The evaporation rate in this case depends on water and ambient temperature, values of (Ta), as in the previous calculations, were applied for Az-Zubeidat village.

Figures (4.19) and (4.20) show the variation of temperatures at locations on conventional and enhanced solar stills without their glass covers. They show that the temperature of the basin is the maximum compared to the water and vapor temperatures, this allows heat to transfer from basin to water to transfer water into vapor, this vapor will move upward by free convection to the ambient. Compared with previous cases this moving vapor do not have to condensate, so the rate of heat transfer from the water surface would be more and the rate of evaporation would increase.

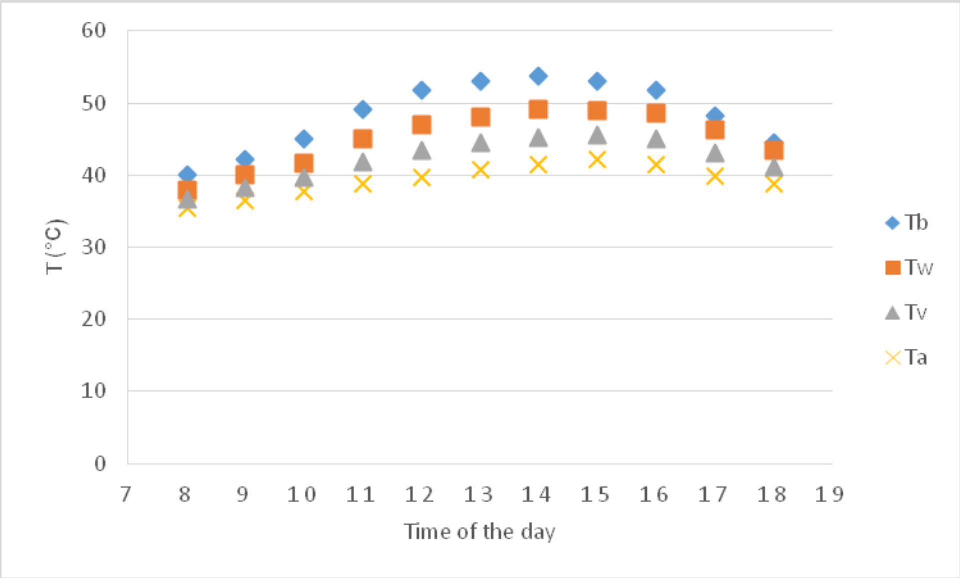

Figure 4.19: Temperatures variation between different locations on the conventional still without the glass cover considering variable parameters.

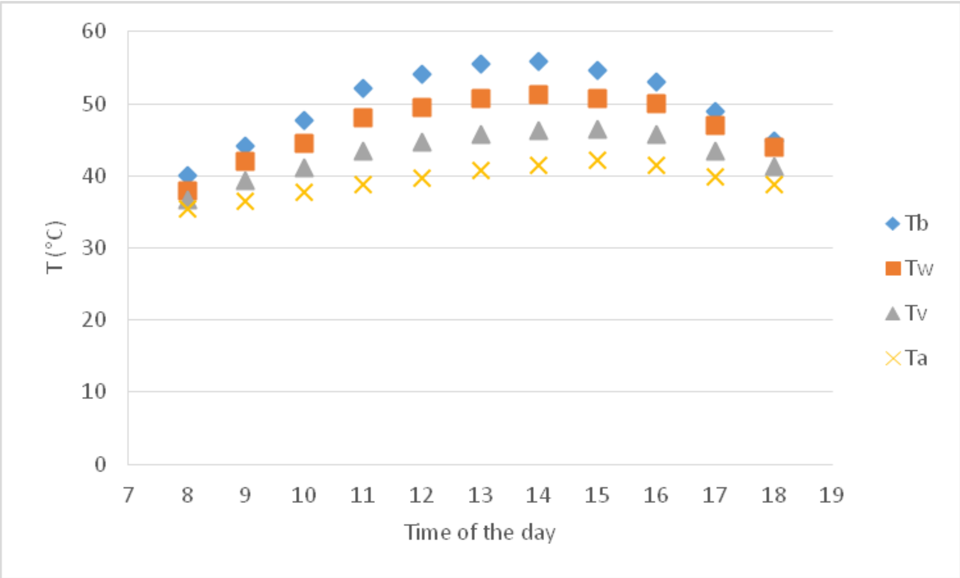

Figure 4.20: Temperatures variation between different locations on the enhanced still without the glass cover considering variable parameters.

Results show that the rate of evaporation from conventional still increased from (1.8 kg/m^2.day) to (4.5 kg/m^2.day) after removing the glass cover, while the evaporation from the enhanced still increased from (3 kg/m^2.day) to (6.7 kg/m^2.day) and the rate of evaporation during the day increased as it is shown in figures (4.21) and (4.22).

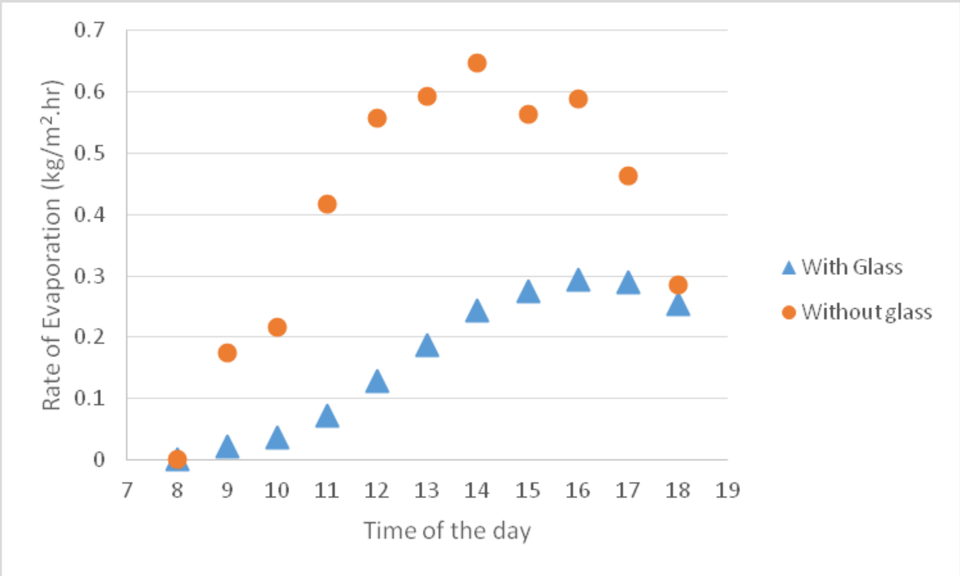

Figure 4.21: Rate of evaporation from the conventional still with and without the glass cover considering variable parameters.

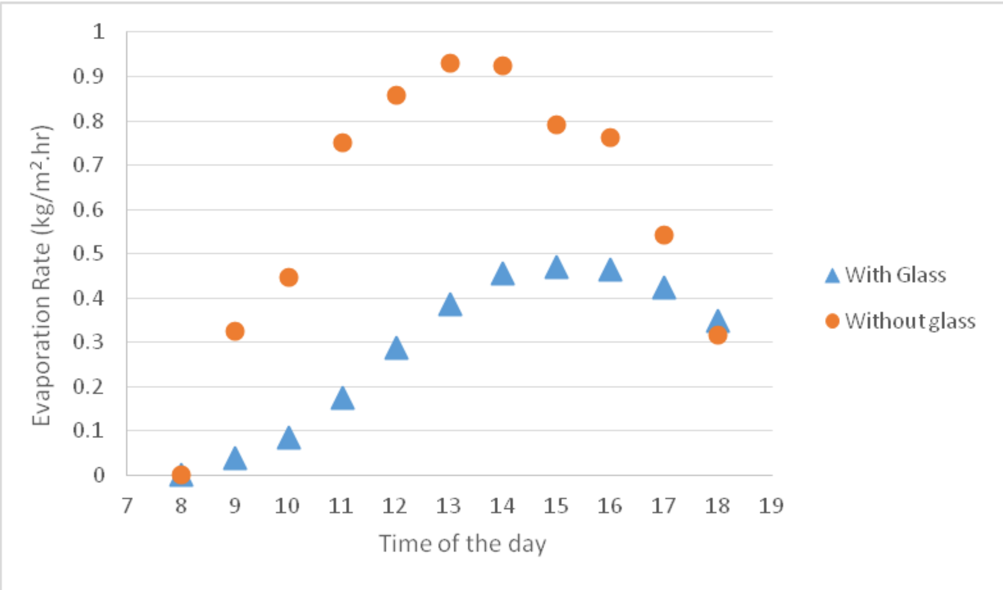

Figure 4.22: Rate of evaporation from the enhanced still with and without the glass cover considering variable parameters.

Figure (4.23) show that the amount of water evaporates from the enhanced still without glass cover is more than it from ordinary still without glass cover, which mean that more water is evaporating and brine volume in the basin is decreasing.

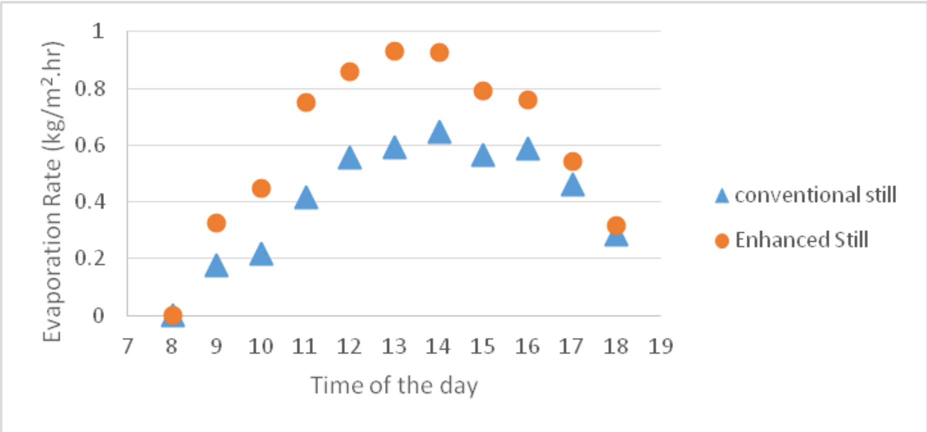

Figure 4.23: Rate of evaporation of conventional and enhanced stills without the glass cover considering variable parameters.

All the previous results proved the idea of using evacuated tubes collector to increase the output from the ordinary solar, and by removing the glass cover the rate of evaporation from enhanced still increases by about 100%.

Az-Zubeidat desalination RO station has a recovery about of 65%, this value is lower that the ordinary recovery values of RO plants (70-85%), so a second RO stage should be added in order to increase the efficiency of this station, this second stage would has a 50% recovery percent.

This station has a daily production rate of a bout (10 m^3/day) so the input would be about (12.1m^3/day) producing (7.9 m^3/day) from the first stage and (2.12 m^3/day) applying mass balance equation, and the rest about (2.1 m^3/day) as a brine stream.

- For suggested hybrid system, it could be applied easily in this village due to the high ambient temperature and availability of solar energy there. The (2.1 m^3/day) retentate could be used as a feed for this hybrid system. For example if 40 houses were included in the project, each house would have 2 m^2 of this hybrid system with glass cover and 1m^2 without glass cover, the optimum depth in this case is 2.65 cm for first 2 m^2. The first 2 m^2 will produce 8.2 L/day for indusial use, the rest 44.8L brine then moved to the second 1 $m^2$for free evaporation, the system will evaporate about 6.7 L/day. In this case this system will provide more fresh water in addition to minimize the brine volume needed to be transferred to the dead sea. The total volume reduction in this case would be 28%.

- As a result for the maintenance problems and operation problems in the RO plant in this area, the second option is to apply the hybrid system for individual use to produce potable water, each 1m^2 would produce 4.1 L/day which is suitable amount for house uses in our study area.

- The hybrid system could be used out of our case study, for example in some houses simple and small RO units are used for producing potable water, the retentate from this system could be treated using this hybrid system to produce more fresh water instead to dispose in the sewer system.

Chapter Five
Conclusions and Recommendations

5.1 Conclusions

The mathematical model equations presented in this research can be used to study the daily output from the conventional and enhanced stills; also, they can be used for studying the effect of solar radiation, ambient temperature, water depth, wind speed, glass cover properties on the output water from the still.

Some of the conclusions are as follows:

1. The proposed study indicates a method to increase the productivity of solar still effectively.

2. The water temperature increases when additional heat energy was added from evacuated tube collectors, which in turn increased the productivity of the solar still.

3. The still output is a strong function of temperature difference between the water in the basin and the glass cover, as the difference increases the output increases.

4. At wind speed =1 m/s the total output water was 3.14 (kg/m^2) and at wind speed = 3 m/s it was 4 (kg/m^2) and it was 4.39 (kg/m^2) at wind speed = 5 m/s which means that the increasing in wind speed will lead to a higher productivity due to the higher temperature difference occurred. A cooling

of the outer side of the glass by outer fan in order to increase the air movement on the surface of the glass will increase the productivity.

5. When the depth in the basin was 3 cm the output water was 4.3 (kg/m^2), it decreased to 3.13 (kg/m^2) as the water depth increases to 5 cm, and when the water depth was set to be 10 cm the output from the still decreased to 1.7 (kg/m^2), it is clear that the water depth has an inverse effect on the productivity. Lower water depth still produces more water.

6. Removing the glass cover increases the evaporation rate from the still to 6.7 (kg/m^2) with about 100% increasing ratio from the still with the glass cover.

7. Using enhanced still for producing drinking water for individual use in Az-Zubeidat village would be effective.

5.2 Recommendations

1. Different geometries of passive solar still could be studied briefly in order to increase the amount of reached solar energy to the water surface.

2. The values of constants in Gr and Pr numbers calculations were set theoretically depends on literature, an experimental work may be carried out on a particular model of stills for given climatic conditions to evaluate these values from a thermal model.

3. The accuracy of the model could be evaluated by conducting an experimental work using the proposed design, and comparing the results with the theoretically obtained results.

4. The properties of glass basin and insulation could be changed and studied for other materials especially new innovative materials based on Nano technology.

5. A monthly solar intensity could be used to calculate the output from the solar still for all days instead of one day.

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جامعة النجاح الوطنية

كلية الدراسات العليا

نمذجة نظام تقطير ماء شمسي مدعم بأنابيب مفرغة من أجل تقليص حجم المياه شديدة الملوحة الناتجة عن عملية التناضح العكسي المستخدمة في تحلية المياه

إعداد

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قدمت هذه الأطروحة استكمالا لمتطلبات الحصول على درجة الماجستير في هندسة المياه والبيئة بكلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس- فلسطين.

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الملخص

في السنوات الأخيرة ونتيجة للزيادة المستمرة في الطلب العالمي على مياه الشرب أصبح النقص في المياه العذبة يشكل تحديا كبيرا للمجتمع البشري. يبدو ان تحلية المياه تشكل حلا مناسبا لإنتاج المياه، ولكن من ناحية أخرى، يعتبر نقص الطاقة التقليدية اللازمة لتكنولوجيا تحلية المياه التحدي الثاني للمجتمع البشري بالإضافة إلى القلق المتزايد تجاه مشكلة التخلص من المياه شديدة الملوحة الناتجة من هذه العمليات.

تعتبر الطاقة الشمسية أفضل بديل لتحويل المياه المالحة إلى مياه صالحة للشرب، أصبحت هذه التكنولوجيا ذو شعبية عالية في المجتمع العلمي بسبب مبدأ العمل البسيط وانخفاض التكاليف واعتمادها على الطاقة الحرة والمتاحة بشكل كبير. لكن العيب الرئيسي لهذه الطريقة هو أن كمية المياه العذبة المنتجة منها قليلة.

يهدف هذا البحث إلى دراسة تأثير إضافة الانابيب المفرغة الى النظام الشمسي التقليدي، وتمت دراسة عدة نماذج مختلفة للنظام الهجين، نموذجا للنظام التقليدي، نموذجا للنظام التقليدي مدعم بأنابيب مفرغة، نموذجا للنظامين السابقين ولكن بإزالة الغطاء الزجاجي. جميع هذه النماذج تم دراستها في حالتين مختلفتين الأولى ان تكون خصائص مكونات النظام ثابتة على طول الفترة الزمنية بينما في الحالة الأخرى تم اعتبارها متغيرة بتغير درجة الحرارة.

بعد الحصول على النتائج من حل النماذج السابقة، أظهرت النتائج أن إضافة الانابيب حسنت من أداء النظام الشمسي بنسبة 48% و73% في حالة اعتبار الخصائص ثابتة او متغيرة على التوالي.

بعد دراسة النماذج السابقة تم دراسة تأثير بعض العوامل مثل عمق الماء وسرعة الرياح على إنتاجية النظام الشمسي وأظهرت النتائج أن هذه العوامل تؤثر على درجة حرارة الماء ودرجة حرارة الزجاج والإنتاجية حيث انه مع زيادة عمق المياه الإنتاجية سوف تنخفض بينما تزيد سرعة الرياح الإنتاجية.

النموذج الجديد الذي تم عرضه في هذا البحث، هو لنظام شمسي تقليدي مدعم بأنابيب مفرغة ولكن من دون الغطاء الزجاجي، وأظهرت نتائج أن هذا النموذج يعمل على زيادة معدل التبخر بنسبة 100٪ في هذه الحالة مما يؤدي الى المزيد من تقليل حجم المياه المالحة في الحوض.

قد توصلنا في هذا البحث إلى أن فكرة استخدام النظام الشمسي المدعم بالأنابيب المفرغة لخفض حجم المياه شديدة الملوحة في منطقة الدراسة هي طريقة فعالة لأنه لا يقلل من حجم هذه المياه فقط وانما يعمل على انتاج المزيد من المياه العذبة إما من هذه المياه شديدة الملوحة أو من المياه المالحة المتوفرة في تلك المنطقة.