Investigation of Stepwise Basin Solar Still

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ABSTRACT

Industrialization, development in agriculture, urbanization and the growth of population, have increased the demand for fresh water. Lack of potable water is an increasing concern in many parts of the world. For instance, in North Cyprus, as a result of intrusion of sea water into the land's aquifers, there is a considerable lack of edible water. The main reason is over withdrawing of underground water from aquifers. There are different methods for extracting fresh water from salty, brackish or contaminated water and distillation is one of them. Energy is required for distillation, and solar radiation can be utilized for this process. As solar radiation is high in North Cyprus, solar desalination technology would be a reliable option in order to extract fresh water from brackish water.

In this study an effort has been made to increase the freshwater yield in a stepwise basin solar still by using a special design to make chimney effect in order to boost the evaporation. The modified solar still consists of two main separable parts which can be easily separated, a base and steps. Four different configurations i.e., base type (traditional still), base with steps, and a sponge liner with base and steps were studied.

Experiments were conducted for 6 months period (September - May) and solar still with base, steps and sponge liner produced the maximum amount of water per day in all months, which is 5.37 liter/day.m^2.

The present study showed that the amount of distilled water increased by each modification.

Keywords: Solar Still, Modified Solar Still, Fresh Water Distillation

ÖZ

Sanayileşme, tarımda gelişme, kentleşme ve nüfus artışı, tatlı suya olan talebi artırmıştır. İçilebilir su eksikliği, dünyanın birçok yerinde artan bir kaygıdır. Örneğin, Kuzey Kıbrıs'ta, deniz suyunun yeraltı akiferlerine girmesi, önemli miktarda içilebilir su eksikliği yaratmıştır. Temel neden yeraltı akiferlerindeki suyun fazladan çekilmesidir.

Tuzlu, acı ve kirlenmiş sudan tatlı su elde etmenin farklı yöntemleri vardır, damıtma bunlardan birtanesidir. Damıtmada enerjiye gereksinim vardır, ve güneş enerjisi damıtmada kullanılabilir. Güneş radyasyonunun Kuzey Kıbrıs'ta yüksek olması, tuzlu ve acı sudan tatlı su elde etmede güneş enerjisi damıtma teknolojileri güvenilir bir seçenektir. Dört farklı konfigürasyon çalışıldı; basit sera tipli (havuzlu) damıtma, basamaklı sera tipi damıtma, havuzlu ve basamaklı sera tipi damıtma, ve havuzlu basamaklı ve süngerli sera tipi damıtma.

Bu çalışmada, güneş enerjili, basamaklı basit sera tipi damıtma sisteminde tatlı su verimini artırmak için buharlaşmayı artıran baca etkisi için özel bir tasarım uygulandı. Modifiye edilmiş basit sera tipi damıtma sistemi kolayca ayrılabilir iki ana parçadan oluşmaktadır, basamaklar ve havuz.

Altı ay (Eylül-Mayıs) boyunca deneyler yapıldı, havuzlu basamaklı ve süngerli damıtma sisteminden tüm deneylerde en yüksek verim alındı ve mayıs ayında en yüksek üretim 5.37 litre/gün.m^2 olarak ölçüldü.

Bu çalışmada güneş enerjili sera damıtma sisteminde yapılan her değişiklik neticesinde damıtılan suyun miktarının arttığı gözlemlendi.

Anahtar Kelimeler: Güneş Enerjili Sera Tipi Damıtma, Değiştirilmiş Güneş Enerjili Sera Tipi Damıtma, Tatlı Su Damıtması

This thesis is dedicated to my parents for their love, endless support and encouragements. It is also dedicated to my wife, without whom I could not have completed this work.

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INTRODUCTION

1.1 The Importance of Clean Water

Good health affects the economic and social development of any nation and clean water is necessary to achieve that. There are many waterborne diseases and consuming contaminated water will endanger the health of people and makes them less active in economic activities. On the other hand, many resources that could be spent on different developmental projects will be wasted on curing diseases which causes retardation in growth of the economy.

Today, one important problem in the world is the lack in supply of potable water for household needs and the lack in availability of sanitation facilities in poor countries. United Nation's Human Development [1] reported this and it has been mentioned that more than one billion people do not have access to clean water, and about 2.6 billion with lack of access to decent sanitation facilities. Annually 1.8 million children deaths from water-borne diseases are reported which could be prevented by using proper sanitation facilities [2].

However, access to edible water, which has standard quality of physical, chemical and biological constituents, is limited. More than 97% of the water, which can be found on the surface of the earth is salty [3], and on the other hand, fresh water resources are degrading due to environmental pollution.

The WHO (World Health Organization) in 2008 reported that 96% and 78% of urban and rural populations had access to clean water in 2006 on a global scale. Annually around 4 billion cases of diarrhea are reported and 88% of them are as a result of using contaminated water, and not enough sanitation and hygiene [4].

So it is clear that providing clean water is necessary. The millennium development goals have set a target to decrease the amount of population which does not have access to clean water by 50% by the year 2015 [5]. This requires development of appropriate technologies to provide clean water which can be achieved through using different approaches and in order to provide fresh water in large amount a sustainable source of energy is required.

Recently, excessive use of non-renewable energy resources has grown many concerns about environmental degradation. Greenhouse gasses (GHG) has caused global warming which created as a result of anthropogenic activities [6]. Emission of carbon dioxide from burning fossil fuels is contributing to this climate change [7]. Parry et al. [8] reported that the impacts of GHG on climate change can be clearly seen. Reducing environmental degradation can be achieved by applying renewable energy technologies to provide clean water.

1.2 Some Conventional Methods of Desalination

Removing minerals, salt and organisms from water is called desalination. And this process requires extensive amounts of energy which is necessary for most of the process. Moreover these systems require specific and rare materials which are expensive [9].

Conventional techniques for water desalination can be categorized into membrane and thermal base [10]. Former types of desalination techniques include Multi-effect distillation (MED), Multi-stage flash (MSF), Multi-effect evaporation (MEE) and vapor compression distillation (VCD) which latter types include nanofiltration (NF), Reverse Osmosis (RO) and electrodialysis (ED). In thermal desalination, water is evaporated and condensed in order to remove the salt. In membrane techniques, water will diffuse through a membrane and a very high proportion of the salt is removed. But these techniques are very energy demanding and are not suitable for low demands of clean water [11]. According to Bouchekima et al. [12], desalination of water in areas with water demands below 50 m^3 daily have been made easier with improvements of the technology in solar distillation. However, productivity of solar stills need to be improved and should be more affordable especially in developing countries. In a report from UN in 2008 [13], regions with developing economies including Asia, Africa and Pacific (excluding Japan, New Zealand, Australia and Commonwealth Independent States of Asia) and Latin America have limited access to edible water. In Africa region access to clean water was very limited in 2006 (82% in urban areas and 46% in rural areas) [14]. According to MukaddasOnen [15], that she investigated the feasibility of MSF and MEE desalination systems for N.Cyprus condition it was discovered that for MSF systems, backed up by solar thermal, the unit cost of water production is reduced to 1.24$/m^3 and for MEE systems to that of 1.69$/m^{3}for a 35000 m^3/day production capacity.

1.3 Distillation with Solar Still

Solar water distillation dates back to over 2000 years ago and it has a very long history but salt was produced instead of clean water. In 1874, in Chile a large scale solar still was built, in order to supply clean water for a mining community. During the Second World War 200,000 inflatable plastic stills were built for the US Navy to be kept in life rafts which were the first mass production of solar stills [16].

Solar still is a device that extracts clean water from saline or brackish water by using solar energy. The concept of this method is quite simple. Figure 1.1 is showing a simple solar still design. Solar still will capture the evaporated water and then condenses the vapor on a cool surface, increasing the contact area of water and the air and increasing the water temperature will increase the speed of evaporation [17].

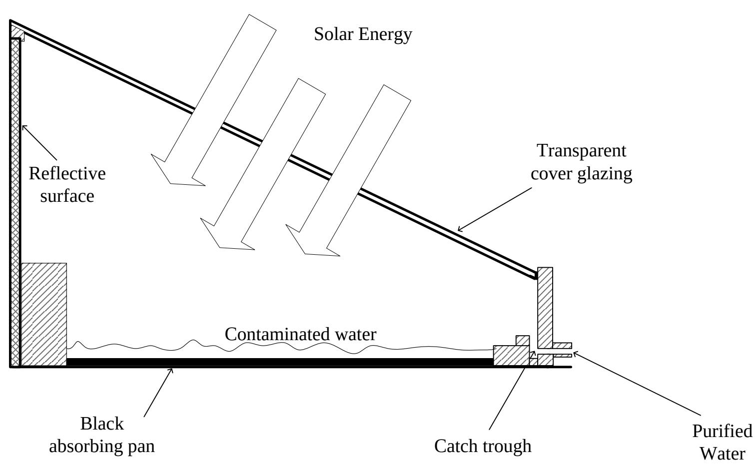

Figure1.1 A Simple Solar Still Design

1.4 Motivation

Shortage of potable water is a noticeable problem in the world. Small production systems such as solar stills can be used if fresh water demand is low and the land is available at low cost. Solar still is a simple device, easy to build, has no moving parts and it is easy to maintain. Solar stills have low energy, materials and maintenance costs. The distilled water from a solar still is ultra-pure water. On the other hand, high fresh water demands make industrial capacity systems necessary which are expensive and usually require skilled personnel to run such systems. One of the disadvantages of using conventional solar stills is that their fresh water production per unit area is relatively low (3-4 Lit/day.m^2) [18]. It is important to improve the efficiency of the conventional still as the yields are low. Therefore modifications are necessary to get better yields.

1.5 Thesis Objectives and Organization

The productivity of a still is affected by the ambient, operating and design conditions. Ambient conditions include ambient temperature, solar radiation, wind velocity and etc. Operating conditions include water depth, inlet water temperature and the orientation of the still. The design conditions are materials selection, glazing slope and type, distance between the glazing and water and etc. Ambient conditions are uncontrollable. For an optimum design the requirements of the design and operating conditions should be satisfied. The effect of ambient temperature on the productivity of a solar still is investigated by several researchers [19]. Al-Hinai et al. [20], investigated the effect of tilt angle, insulation thickness, and water depth. Reducing the distance between the glazing (condensing cover) and the evaporating surface improves the performance of a solar still. Reducing the distance between the condensing cover and evaporating surface reduces the time of the evaporated water to reach the condensing cover. Therefore quicker air movement is established in the still. Stepped solar stills were investigated by many researchers such as Radhawan [21]. The distance between the cover and the evaporating surface is reduced in stepped solar stills.

The stepwise basin solar still with special design to make chimney effect in order to boost air circulation has not been studied before.

The main objective of this study is to design, build and experimentally investigate the modified solar stills (including stepwise basin solar still having chimney effect) and compare the modified stills with the conventional still under climatic conditions of Famagusta, Cyprus.

The organization of the thesis is as follows:

Chapter 1 is the introduction into the availability of water, methods of desalination and some information about solar still. Chapter 2 includes literature review on solar stills. Chapter 3 is about the experimental setup of the apparatus and data collection and some information about how it was built. The results and discussions are present in chapter 4. Finally conclusion and suggestions are given in chapter 5.

Chapter 2

LITRETURE REVIEW ON SOLAR STILLS

2.1 Water Desalination

Land-based plants and ships have used distillation technologies for a century in order to provide edible water for their crew. After World War II, the use of these technologies accelerated as the need for fresh water was increased. During the past years the cost of distillation plants has decreased because of introduction of new and more efficient technologies. Distillation can be used to purify water and in order to power distillation devices solar radiation can be used. Sunlight is a sustainable energy and has no fuel cost but in order to collect it more space is required and the equipment used is more costly [18].

2.2 Solar Still

The same process that happens naturally that creates rainfalls is used in solar stills. In solar stills saline water is collected inside a pan, which is covered by a transparent cover, which heats up the water and causes it to evaporate and the water vapor will then be condensed on the inner face of the sloping transparent cover. The result is generally potable with a high quality, because all the extra components of the water like salts and microbes are left in the basin. And all pathogenic bacteria will die as a result of high temperatures of sunlight [1].

In terms of energy supply solar distillation systems are categorized in two groups: active and passive solar stills. In active solar systems an external thermal energy such as waste thermal energy from industrial plants or a solar collector is used to increase the evaporation and passive solar still systems rely only on solar energy as the only source of thermal energy. Basin-type solar still systems have different structures and can be found in literature [2].

2.3 Development of Solar Still

In order to convert brackish water into edible water Single basin solar still is generally used. But since its efficiency is low it is not very popular. There have been a number of researches in order to increase the efficiency of solar still, which depends on many factors such as solar radiation intensity, location, temperature, basin water depth, thickness of the basin, glass cover material, heat capacity of the still and wind velocity [22].

Many designs have been developed in order to increase the performance of solar stills such as multi-basin type [23], double-basin type [24], a wick basin type [25] and multi-use environmental type [26]. Many parameters will affect the annual performance, which have been studied as well [27]. Also, effects of mass flow rate of water in heat exchanger loop, heat exchanger length and water depth in basin have been studied as well [28].The effect of augmentation of the productivity of the solar still by using black gravel and black rubber has been studied as well [29].

Additionally in order to modify solar still, many improvements have been proposed which include, use of greenhouse, sponge cubes, reflectors, an external condenser, sun tracking, phase change material which are integrated into solar stills and flat plate solar collectors [18].

2.4 Relevant Historical Review

There are a large number of papers, researches and experiments on solar still desalination process from different aspects. Accordingly, some of them have been listed in following part, which are relevant to this study.

Samee M. et al. [30] designed a simple single basin solar still for experimenting at PIEAS, Islamabad. Average solar insolation on horizontal surface in Pakistan is nearly 200-250 W/m^2 with approximately 1500-3000 sunshine hours in a year. The glass cover angle was 33.3^o in their experiment. A schematic of this solar still is illustrated in Figure2.1.

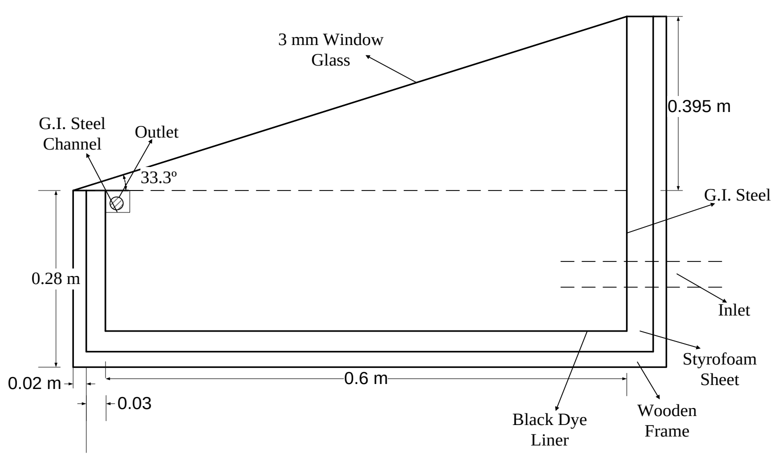

Figure2.1. Schematic Diagram of the Designed Single Solar Still

At the end of 8 days analysis of data in July 2004 indicated an average water production of 3.14 Lit/day.m^2. They suggested that this kind of solar still is useful for rural communities to get potable water from brackish water.

In 2008 a study has been done by hosseinAssefi, [31] which was about review and analysis of solar desalination systems under this scope, this study carried out on modeling and analyzing of a single slope solar still in order to investigate the effect of water depth and inclination angle of glass cover on the productivity of the system. Among the published experimental data, it has been found that highest productivity rate is obtained with solar humidification-dehumidification systems while that of the lowest is obtained by using inclined solar still with bar plate. The total productivity rate of the proposed system under the climatic condition of North Cyprus on 21^{st} of Marc was obtained 5.3 kg/m^2.day the total obtained productivity rates are compared with previous experimental studies and it was discovered that there is a difference of ±3.37 on average.

In 2002 an experimental study of a solar still with sponge cubic in basin was carried out by Abu-Hijleh, B.A, and Rababa'h, H.M, [32]. They designed two similar solar stills and conducted experiments under the same conditions. One solar still included cubic sponge in the basin and the other without sponge. The size of each still base was 50 cm ×50 cm and the glass angle with the box was 23^o. The experiments carried out during the months of September and October at the campus of the Jordan University, Irbid, Jordan. The experiments carried out for 6 hours in a day from 9:00 AM till 15:00 PM. The main focus was to investigate the effect of cubic sponge and parameters which affect productivity such as water depth, type and presence of insulation material was not investigated in this study. An illustration of this work is shown in figure 2.2.

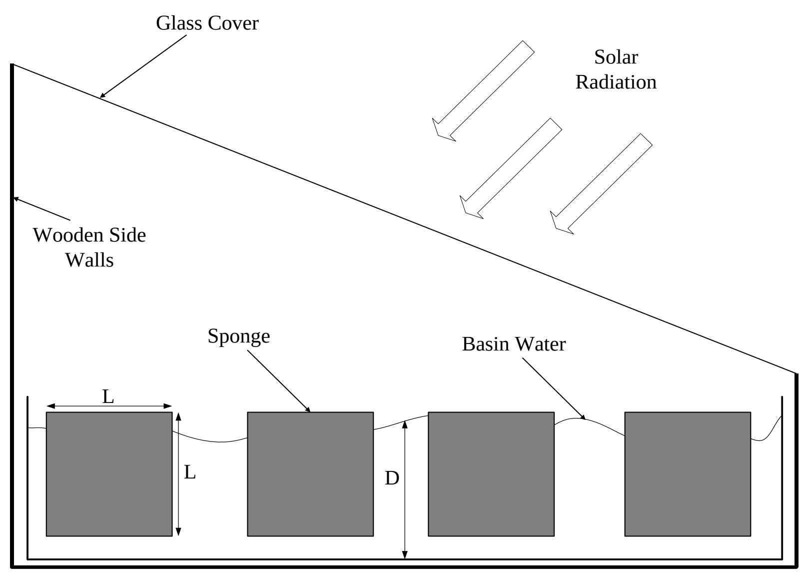

Figure2.2.SideView Schematic of the Solar Still with Sponge Cubes

As a result of this experiment, the improvement in produced water was 273% compared with still having no sponge and the optimal composition was: 7cm basin water depth, 20% sponge to base water volume ratio and also the use 6 cm sponge cubes [32].

In 2012, an Experimental study was carried out by Karuppusamy S, [33] on single basin solar still with evacuated tubes. In this experimental study, he used a single sloped solar still with evacuated tubes to increase the daily production of water by decreasing heat losses. In this study, the solar still has $1m^2$ area and the evacuated tubes directly paired to the bottom of solar still.

To increase the productivity, black gravel was used and the experiment done in several model: still with black stones, still with evacuated tubes, still alone and still with black gravel and evacuated tubes together. At the end of this experimental work it was found that the daily production had an increase after adding the evacuated tubes by 49.7% and with black stone the daily production increased by 59.48% [33].

An experimental study carried out by A.Akash B, et al [34] on a single basin solar still by using different absorbing materials. In their study, a single basin solar still with $3m^2$ area has been used. A glass cover was placed at the top of the solar still which is tilted 25^o with horizontal.

A.Akash B, et al used 3 different models in their experimental study black absorbing rubber mat, black ink –in – water solution and black dye in water solution [34].They found that water productivity increased by 60% when black dye was used. Black ink increased water productivity about 45%.

2.5 Comparison of Systems Productivities

The difference in fresh water productivity rates among solar desalination system is high. Many researches have been conducted by different researchers around the world theoretically and experimentally,in order to investigate and improve the productivity rate of solar stills. Some selected experimental and theoretical studies and their results of different kind of solar stills are collected and present in table 2.1. In this table important factors having great effect on the final yields, like solar intensity, ambient temperature and place of the conducted researches are specified [31].

Table 2.1. Experimental Results of Selected Solar Desalination Systems [31]

Name of the system	Place	Average solar intensity (W/m^2)	Ambient mean temperature (^oC)	Productivity $Lit/day.m^2$	References
Inclined basin solar still with bare plate	North Cyprus,Gazimagusa,EMU	450	30	1.29	[35]
Solar still with aluminum sheet using back wall heat	Bahrain,Bahrain University	850	N/A	1.71	[36]
Single basin solar still with deep basin	Egypt,Tanta University	605	28	2.045	[37]
Forced condensation in the solar still	Bahrain, Bahrain University	512	N/A	2.37	[36]
Inclined basin solar still black fleece	North Cyprus, Gazimagusa, EMU	710	25	2.995	[35]
Simple single basin solar still	Islamabad, Pakistan, PIEAS	250	38	3.14	[30]

The lowest productivity rate is for inclined basin solar still with bare plate with production rate of 1.29 $lit/day.m^2$ while the productivity of this system will be more than doubled by covering the basin with black fleece to the value of 2.995 $Lit/day.m^2$. This system has been tested in Eastern Mediterranean University N.Cyprus [35].

In the next chapter, the experimental setup for the proposed models is explained in detail.

Chapter 3

EXPERIMENTAL SETUP

3.1 System Description

In this study, a conventional solar still was constructed and tested. Then the solar still was modified and tested. These different modifications were experimentally investigated. The experiments were conducted at the Eastern Mediterranean University campus in the Mechanical engineering department. The basin was constructed with galvanized iron sheets of one mm thick which was painted black in order to maximize the radiation heat absorption from the solar radiation.

For the experiments, inedible water was used. The work carried out in September, October, November, March, April and May. The amounts of fresh water production have been recorded. As desalination continues after sunset, in the following morning the amount of distilled water was measured before hourly measurement started.

Each model of this experiment has different structures or components that make it to differ from the others. In order to evaluate the effects on water production of different designs of solar still devices, tests were conducted.

3.2 Configuration of Four Different Models Solar Still Modification:

Four different configurations were built and tested:

1. Conventional Solar still, (Type1) which is shown in (Fig 3.1).

2. Solar still with steps, (Type2) which is shown in (Fig 3.2).

3. Conventional Solar still with steps (both basin and steps include water), (Type3, Fig 3.3).

4. Conventional still with steps and sponge liner, (Type4, Fig 3.4).

This table is showing the major parts of each setup:

Table 3.1.The Major Part of Each Setup

Parts / Model	Wooden Box	Glass Cover	Steps	Sponge	Channel
Type 1	✓	✓	–	–	✓
Type 2	✓	✓	✓	–	✓
Type 3	✓	✓	✓	–	✓
Type 4	✓	✓	✓	✓	✓

In the following there are some pictorial and schematic of each model of this experimental study with a short explanation about each type.Also, their technical drawings are available in appendix.

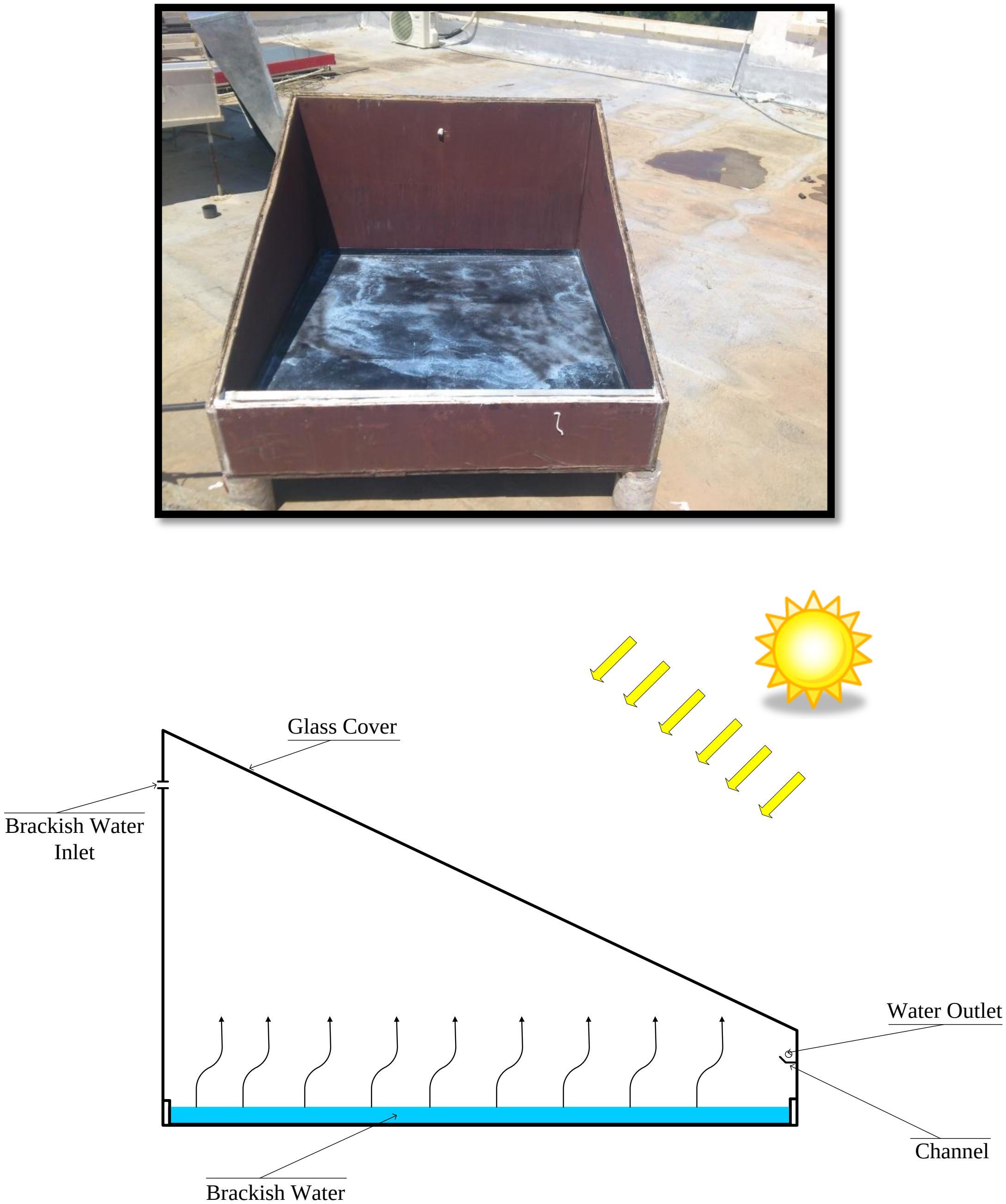

Figure 3.1. Pictorial and Schematic Convention Solar Still

Figure 3.1 shows the solar still type 1 which is consisted of main parts as: wooden box, channel, glass cover and basin. As demonstrated in figure 3.1 the water placed only in basin of the solar still, this model is our basic type of this experimental study.

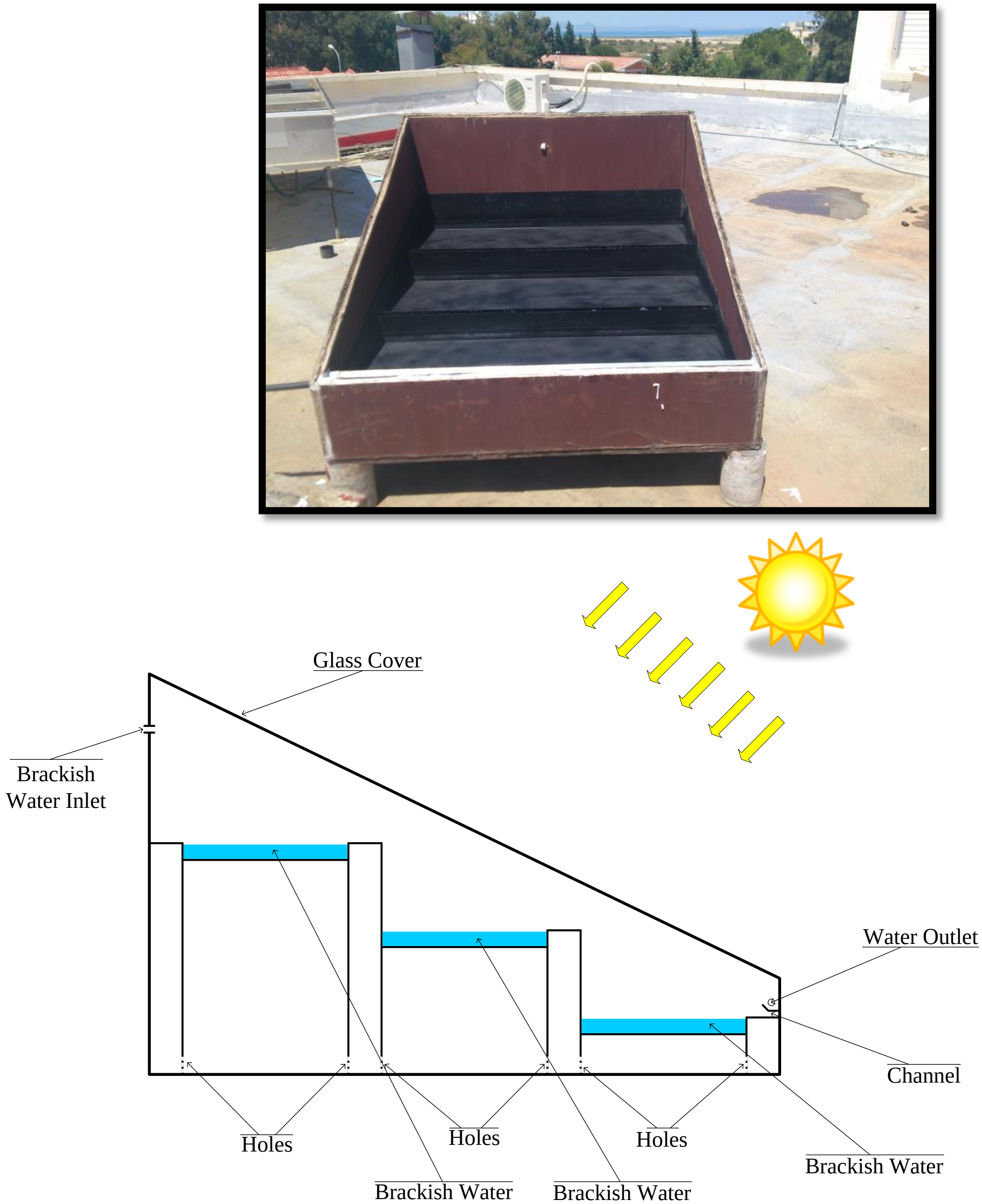

Figure 3.2. Pictorial and Schematic of Solar Still With Steps

Base on the figure 3.2, the additional parts of this type compared to basic model are included threesteps which are exactly similar to each other. Data collection for this type of experiment has been carried out three days in different months from (Sep2012-May2013) with the aim of finding out the variation of obtained water.

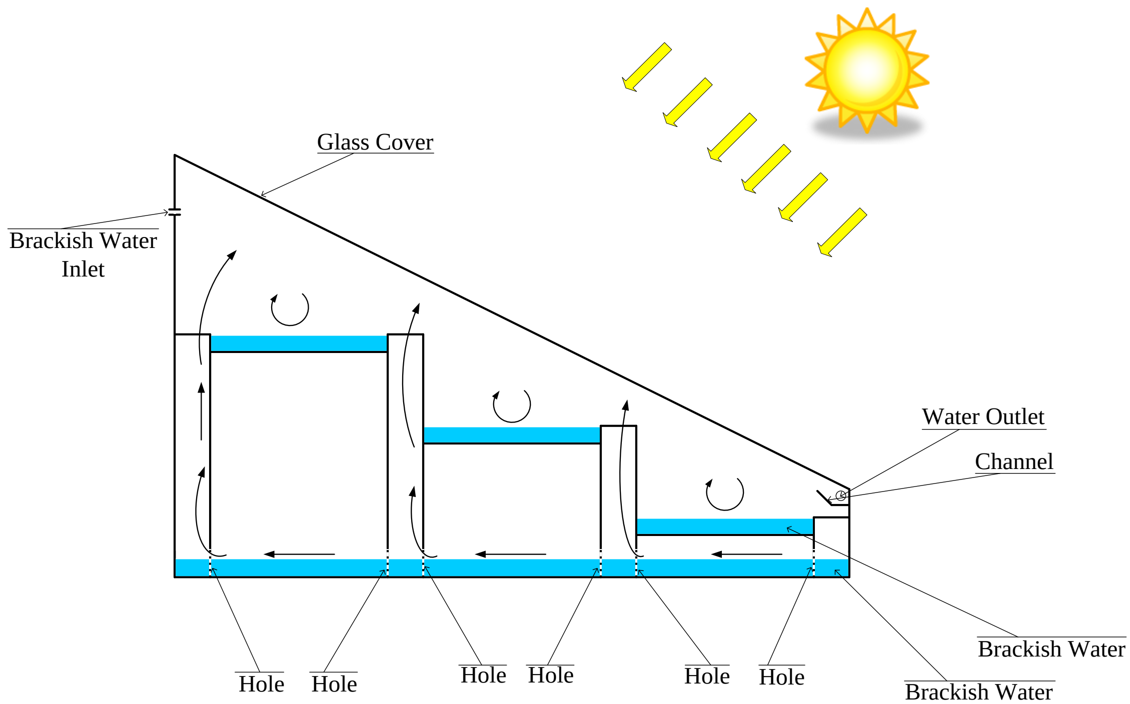

Figure 3.3. Schematic of Solar Still With Steps and Base, Both Include Water

According to the figure 3.3, the third type of this experiment is a combination of type 1(basic model) and type 2, which means in this configurationthere is water in both basin and steps. Also, at the bottom of the steps there are some semi circular holes in order to enable the movement of water and air.

At the exit of holes in the bottom of the steps the hot humid air will moves up due to the existence of chimney effect. At the end this humid air will combined with the evaporated water of steps.So,the result of water production is more than type 2.

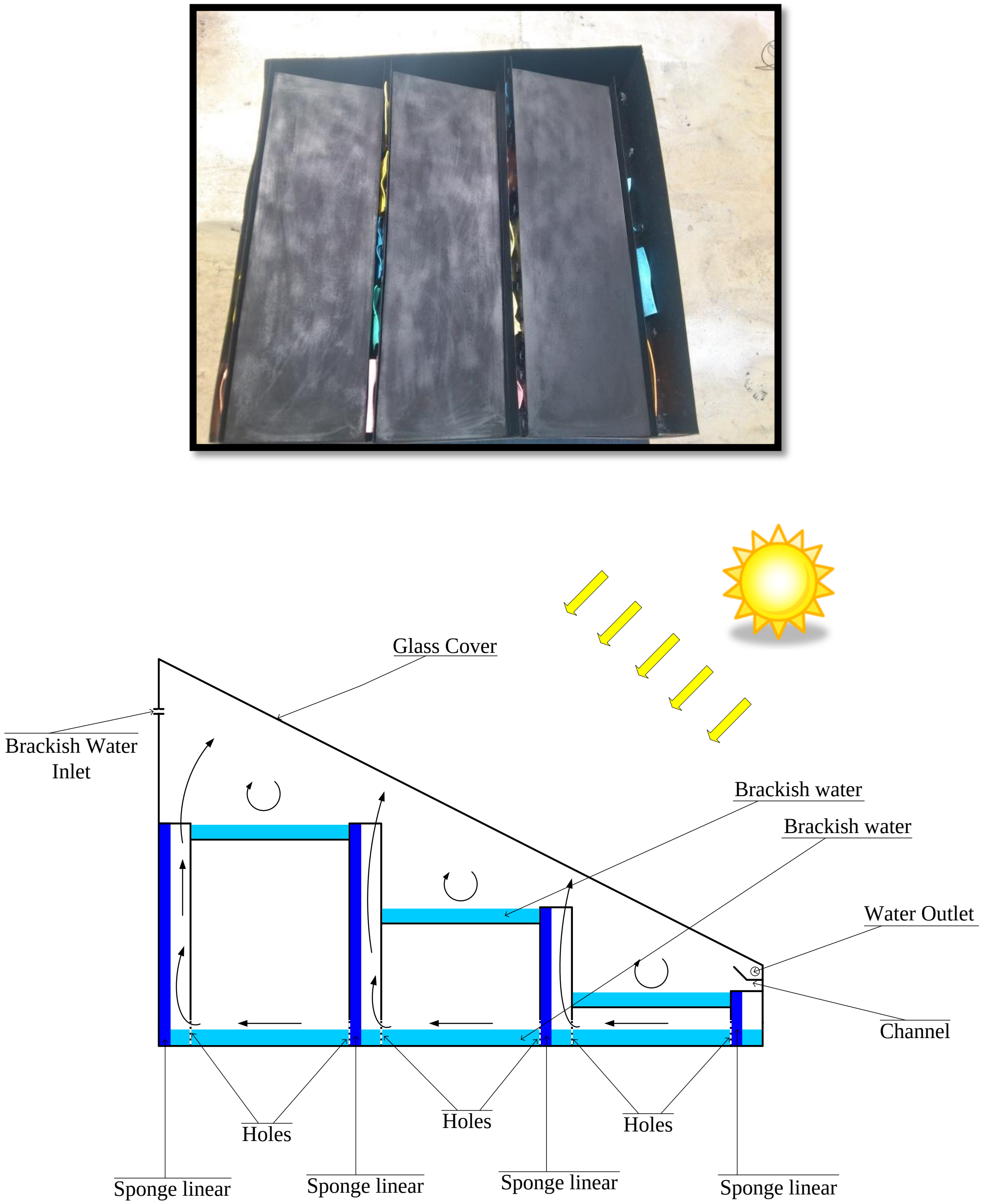

Figure 3.4. Pictorial and Schematic Solar Still with Steps and Sponge

According to figure 3.4, this type is almost similar to previous type (type3) but in this type there are some sponge layer inside the gaps between steps in order to increase evaporation and water production.

3.2.1 Wooden box

In all 4 setups, the wooden box was fixed. It should be noted that all the holes of the wooden box was completely sealed with silicon to prevent the flow of warm air from inside to outside. In addition, a glass with 5mm thickness was used at the top of the wooden box as glazing. The sides were sealed with silicon. Moreover, the glass-cover of solar still makes an angle 24^o with horizontal.

3.2.2 Steps

The steps are introduced to boost the evaporation.

Internal components of the solar still are composed of two separate parts, which include base and steps that can be easily separated from each other. When the steps are on the base, there are several semi-circular holes in the bottom of the steps to enable water and air movement (Fig 3.5).

Figure 3.5. Semi-Circular Holes in the Bottom of the Steps

The distances or gaps, between steps created chimney effect in the solar still, so the warm humid air moves up.

3.2.3 Channel

A galvanized channel has been designed and placed under the lower side of the glass to collect the condensed water. The channel was fixed on the wooden box with great care to completely collect the condensed water vapor droplets into the channel. The channel is connected with a plastic pipe in order to collect the fresh water into an external tank.

3.2.4 Sponge layer

Some sheets of foam with a uniform thickness of 2.5mm, which have noticeable ability in order to absorb water, have been put in the gap between the steps to increase the chimney effect property.

To measure the solar radiation on the cover (surface) of the solar still, an Eppley radiometer Pyranometer has been used, that coupled with a solar radiation meter in model HHM1A digital with resolution of ±0.5%from 0 to 2800 W/m^2 the radiation was recorded hourly.In addition, the temperature recorded hourly by using a digital thermometer (Omega MDssi8 SERIES) with accuracy of ± 1.0(^{o}C). Also, a scaled beaker with accuracy of ± 5 ml has been used to measure the obtained water of all 4 types of solar still. All the devicesare indicated in Figures 3.6 to 3.8.

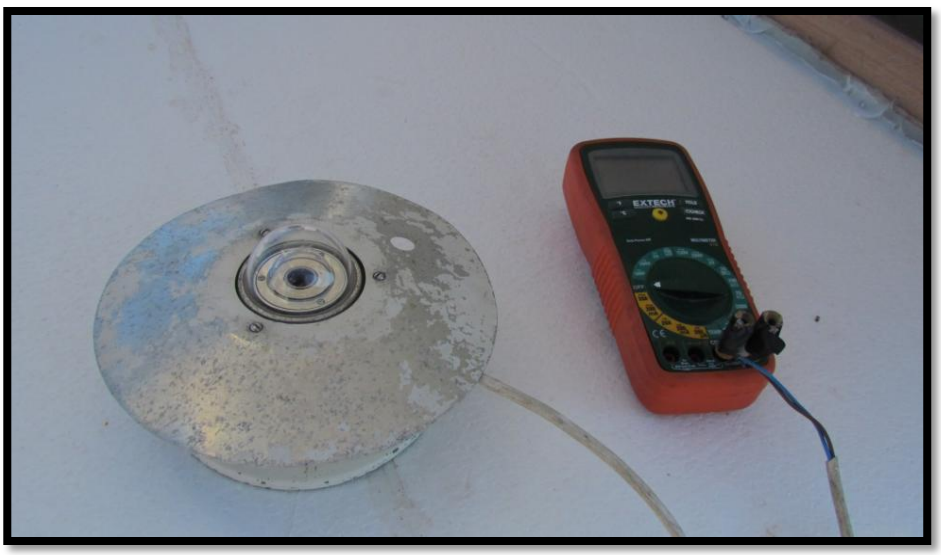

Figure 3.6.Pyranometer

Figure 3.7. Digital Omega Thermometer

Figure 3.8. Scaled Beaker

The results obtained from the tests conducted are presented in following chapter.

Chapter 4

RESULT AND DISCUSSION

4.1 Introduction

Results of this study are reported by using tables and graphs. As mentioned earlier this study carried out under Famagusta climate condition in North Cyprus. Famagusta is located on 35.125^{o}N and 33.95^{o}E longitude.

This experiment were performed in different months the experiments have been done in winter between 8:00-16:00 hours while in summer experiments carried out between 9:00-17:00 hours daily.

4.2 Effect of Solar Radiation and Ambient Air Temperature

The performance (water production) of any solar still depends on different parameters such as, ambient air temperature and solar radiation. There are other parameters which affect water production but these are not investigated in this study.

Ambient air temperature and solar radiation have been measured hourly during experiments and these data are listed in related tables for each month. Each setup of this experimental study was tested for 3 days in different months of the year and the average solar radiation, ambient air temperature and water production have been listed in tables for each month. The solar radiation, ambient air temperature and water production are presented in graphs.

Finally, increase in water production in type 4 is more than 60% in all months compared to type 1.By comparing the first type, which is the base model for this experiment, by other 3 types, the percentage of increase in the obtained water in different months and models has been shown in table 4.1.

Table 4.1. Percent Increase in Water Production Compared with Type 1

Month	**Type 2**	**Type 3**	**Type 4**
September	28.26%	47.31%	62.23%
October	40.89%	64%	80%
November	38.19%	53.94%	76.97%
March	38.47%	55.77%	73.72%
April	35.72%	59.65%	73.58%
May	28.83%	45.35%	61.27%

Table 4.2.Hourly Average Radiation and Ambient Air Temperature for the Months Sep2012 toMay 2013.

Hourly average radiation and ambient air temperature for the months Sep 2012 to May 2013										
Months / Time	September		October		November		March		April	
	Radiation W/m^2	Temperature ^{o}C	Radiation W/m^2	Temperature ^{o}C	Radiation W/m^2	Temperature ^{o}C	Radiation W/m^2	Temperature ^{o}C	Radiation W/m^2	Temperatu ^{o}C
08:00	-	-	-	-	563.5	21.13	485.5	18.9	-	-
09:00	569	26.45	596.8	25.28	638.1	22.1	574.9	20.48	515.66	25.88
10:00	661.9	27.98	726.2	26.8	754	23.8	685	22.45	634.6	27.03
11:00	750	29.08	841.2	28.1	850.1	25.07	790	23.5	733.2	28.15
12:00	847.5	30.28	871.4	29.53	827.7	26.6	865.6	24.85	828.4	29.45
13:00	883.3	31.28	879.3	30.25	744.5	26.05	828.9	24.33	875.3	30.1
14:00	866.7	32.9	836.5	29.08	648.4	25.05	733.5	23.35	830	30.25
15:00	795.3	31.38	691.3	27.88	560.4	24.15	620.1	22.33	740.9	29.15
16:00	697.6	29.9	604.8	27.23	446	23.33	505.5	20.88	638.5	27.7
17:00	590.5	28.45	518.3	26	-	-	-	-	543.1	26.6

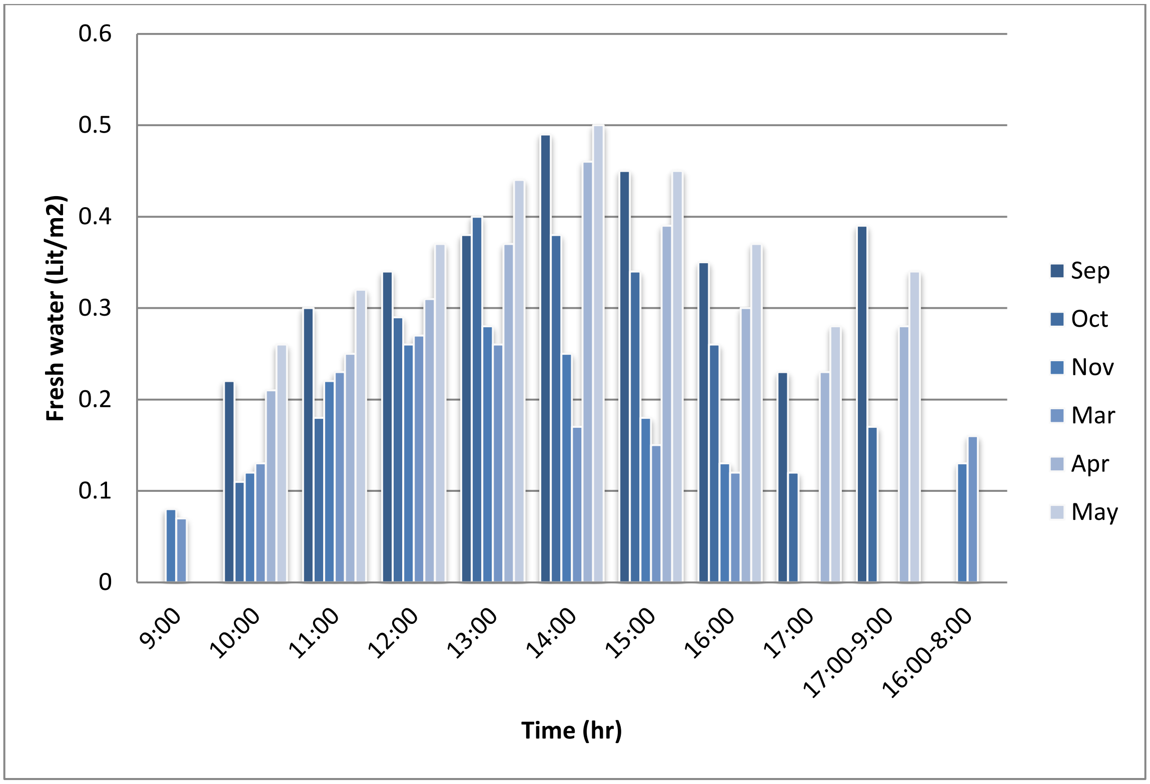

Figure 4.1. Water Production of Type 1 for All Months (Sep 2012-May 2013)

Figure 4.1 is showing the hourly rate of water production in all months of experiment. The rate of water production is varies which is because of the duration of experiment from early morning until late afternoon, since solar radiation and ambient air temperature are changing. According to this diagram, the water production increased to its maximum level around 14:00 in afternoon and after that started to decreased.

The maximum amount of daily water production for type 1 is related to May and the minimum daily water production is related to March, which are: 3.33 Lit/day.m^2 and 1.56 lit/day.m^2 respectively.

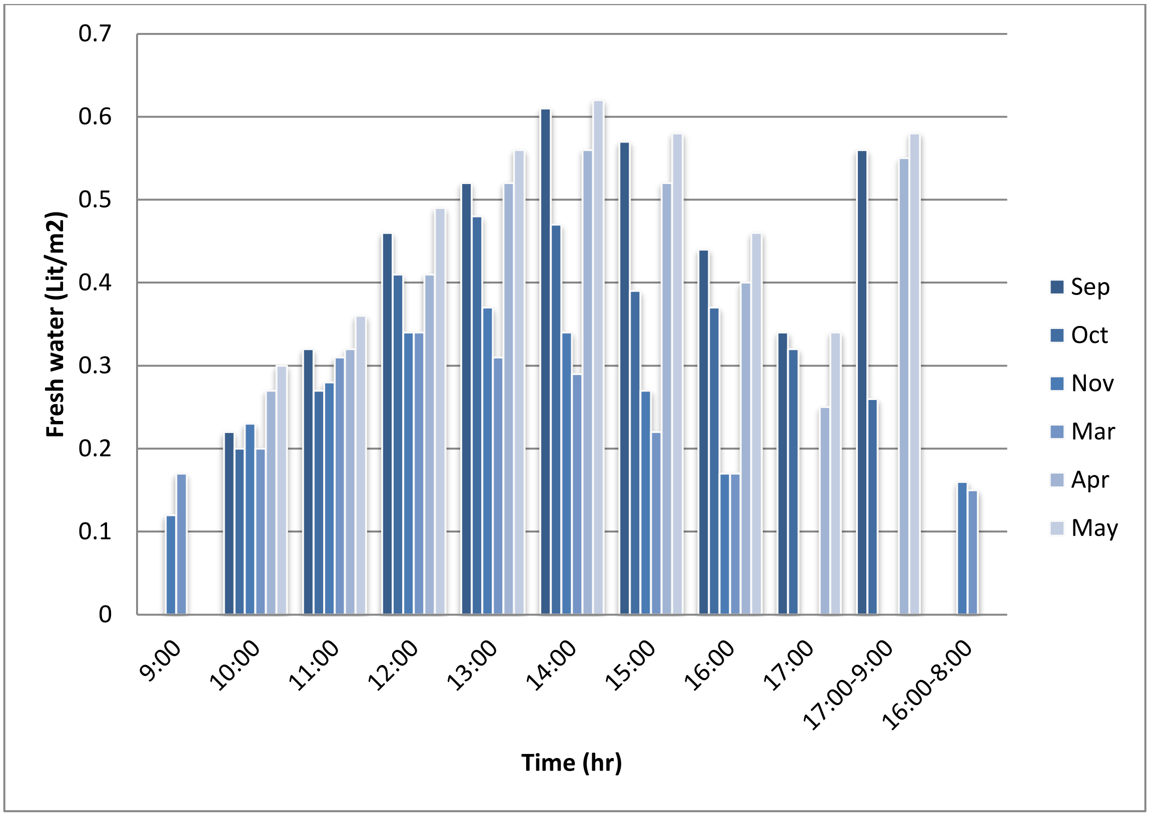

Figure 4.2. Water Production of Type 2 for All Months (Sep 2012-May 2013)

This diagram is showing the water production of type 2 for the all months (Sep 2012-May 2013). According to the diagram above, the most produced water is related to May at 14:00 in afternoon. This obtained water production is close to the result of September at the same time in the afternoon, which is because of the similarity of radiation and air temperature of both months.

In addition, the maximum amount of daily water production is related to May, also the minimum daily water production is related to march, which are : 4.29 Lit/day.m^2 and 2.16 Lit/day.m^2 respectively

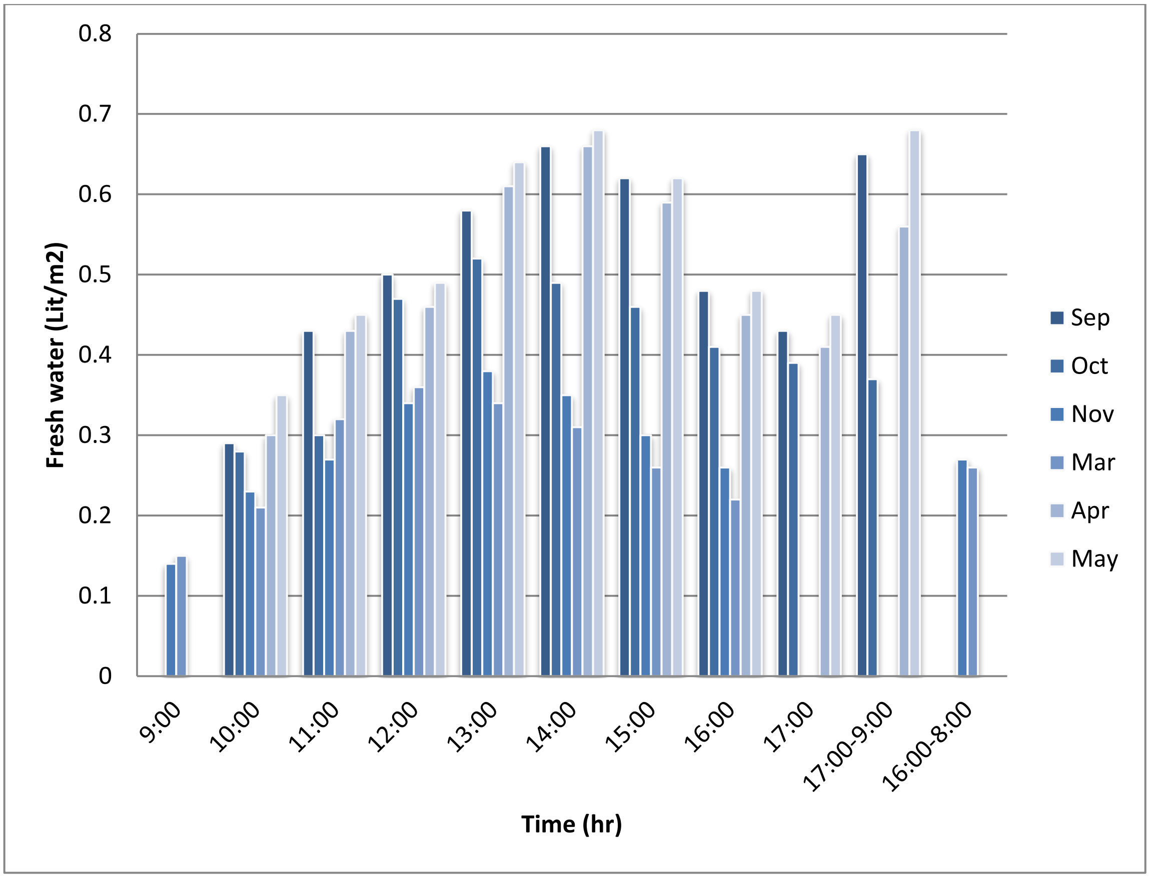

Figure 4.3. Water Production of Type 3 for All Months (Sep 2012-May 2013)

This diagram is showing the hourly water production of all months. According to the diagram, the maximum amount of obtained water is related to May at 14:00 in the afternoon.

Furthermore, the maximum amount of daily water production is related to May and the minimum daily water production is related to March, which are:4.84 Lit/day.m^2 and 2.43 Lit/day.m^2 respectively. The results indicate that the output of this model is more than two previously types.

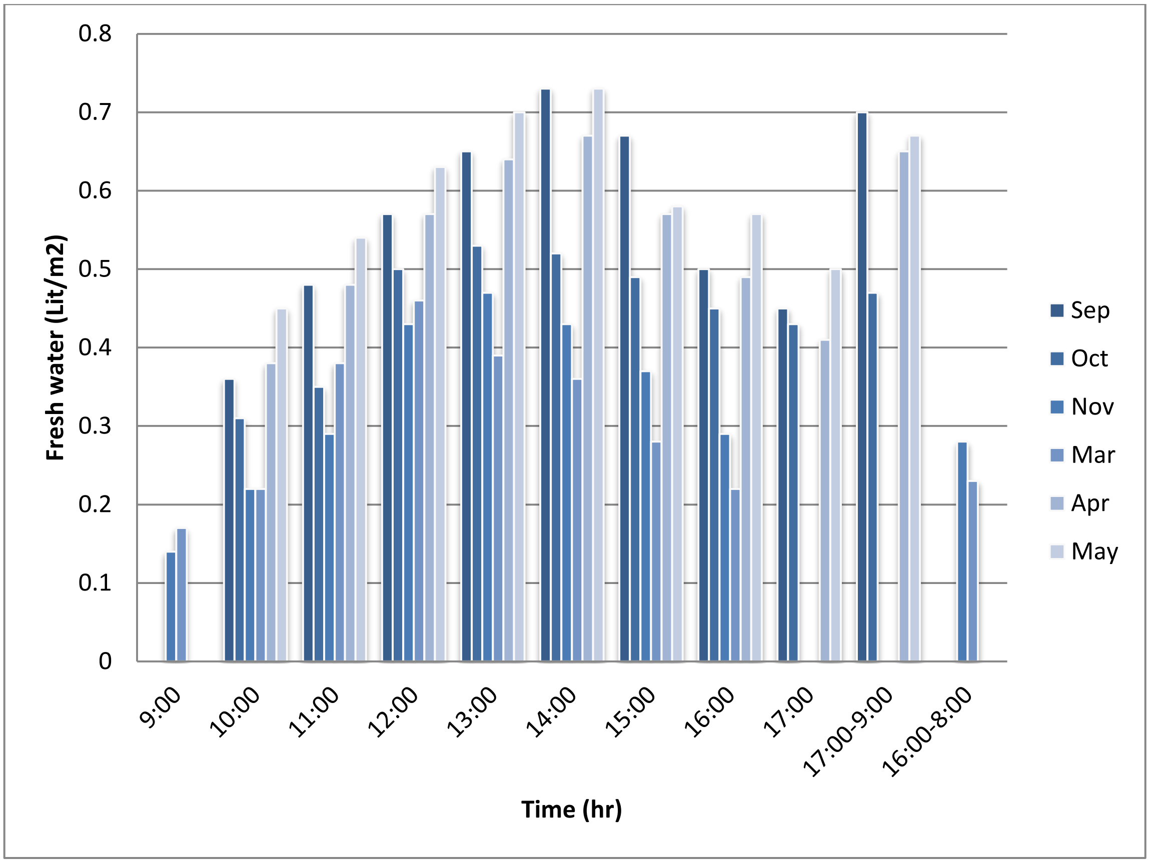

Figure 4.4. Water Production of Type 4 for All Months (Sep 2012-May 2013)

This diagram is showing the hourly water production for type 4, which is the most complete model in comparison with the last three models.Under this scope, in this experiment the most amount of water production was related to this type (type 4).

In addition, the maximum amount of daily water production is related to May with 5.37 Lit/day.m^2, also the minimum daily water production is related to March with 2.71 Lit/day.m^2. This type shows the maximum output among the other types.

Chapter 5

CONCLUSION

This experimental work presents result of 4 (four) different setups of solar stills in different months. Type 1 which is the traditional still tested for 6 months. The maximum daily production was obtained in May, 2013 which was 3.33 Lit/m^2.day.The performance of type 2 was improved due to the usage of steps. The maximum production in type 2 was 4.29 Lit/m^2.day achieved in May 2013 where the solar radiation was highest.

Similarity the maximum daily production for the type 3 and type 4 are 4.84 and 5.37 Lit/m^2.day respectively are obtained in May.

Solar radiation is the important factor that affects productivity of the solar still during the experiment, increasing solar radiation increase the production of potable water. The effect of the ambient temperature on potable water production was not significant.

5.1 Suggestion for Future Work

This experimental study has shown that the existence of gaps between steps and also using sponges between these gaps improve daily water production of solar still significantly.

However the following suggestions could improve stepwise solar still systems' water production:

-The use of different materials at the gaps between steps instead of sponge.

-Testing the effect of sponge thickness and placement of sponges.

-Testing the effect of glass cover thickness.

-Testing the effect of different kind of metal sheets (different materials) to built the steps.

-Using of sun tracking device in order to maximizing the solar radiation.

-Using mirror or mirrors to reflect sunlight into solar still in order to increase the evaporation.

-In order to increase potable water it is necessary to allow more solar energy into solar still by using a low iron glass glassing.

-Solar still can be paired with a solar collector to increase the water temperature inside of solar still.

-Study of water thickness in the basin and steps

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APPENDIX

The hourly radiation, ambient air temperature and water production for each type are presented in the following tables (Tables A.1-A.24) for all months (Sep 2012-May 2013).

Table A.1. Measured Values of September (Type 1):

Time	**Radiation** W/m^2	T_{amb} ^oC	**Water Production** Lit/m^2
9:00	580.9	26.5	-
10:00	647.6	27.5	0.22
11:00	771.4	28.3	0.3
12:00	885.7	29.9	0.34
13:00	923.8	31.2	0.38
14:00	857.1	32.6	0.49
15:00	790.4	30.1	0.45
16:00	723.8	28.7	0.35
17:00	600	27.6	0.23
17:00-9:00	-	-	0.39
Ave	753.4	29.15	-
			Tot = 3.15 $Lit/m^2.day$

Table A.2. Measured Values of September (Type 2):

Time	**Radiation** W/m^2	T_{amb} ^oC	**Water Production** Lit/m^2
9:00	552.3	25.6	-
10:00	695.2	27.7	0.22
11:00	790.5	28.9	0.32
12:00	857.1	29.6	0.46
13:00	895.2	30.2	0.52
14:00	790.4	31.3	0.61
15:00	752.4	30.7	0.57
16:00	647.6	29.8	0.44
17:00	552.4	27.8	0.34
17:00-9:00	-	-	0.56
Ave	725.9	29.06	-
			Tot = 4.04 $Lit/m^2.day$

Table A.3. Measured Values of September (Type 3):

Time	**Radiation** **W/m²**	**T_{amb}** **^{o}C**	**Water Production** **Lit/m²**
9:00	542.8	27.3	-
10:00	657.1	28.5	0.29
11:00	742.9	29.6	0.43
12:00	809.5	30.9	0.5
13:00	847.6	32.5	0.58
14:00	914.3	34.5	0.66
15:00	790.5	32.6	0.62
16:00	704.7	31.3	0.48
17:00	600	29.7	0.43
17:00-9:00	-	-	0.65
Ave	734.4	30.76	-
			Tot = 4.64 $Lit/m^2.day$

Table A.4. Measured Values of September (Type 4):

Time	**Radiation** **W/m²**	**T_{amb}** **^{o}C**	**Water Production** **Lit/m²**
9:00	600	26.4	-
10:00	647.6	28.2	0.36
11:00	695.2	29.5	0.48
12:00	838.1	30.7	0.57
13:00	866.6	31.2	0.65
14:00	904.7	33.2	0.73
15:00	847.6	32.1	0.67
16:00	714.3	29.8	0.5
17:00	609.5	28.7	0.45
17:00-9:00	-	-	0.7
Ave	447.06	29.97	-
			Tot = 5.11 $Lit/m^2.day$

Table A.5 .Measured Values of October (Type 1):

Time	Radiation W/m^2	T_{amb} ^{o}C	Water Production Lit/m^2
9:00	590.5	25.7	-
10:00	787.3	27.5	0.11
11:00	879.3	28.8	0.18
12:00	892	29.3	0.29
13:00	920.5	30.8	0.4
14:00	828.5	28.8	0.38
15:00	584.1	27.8	0.34
16:00	495.2	27.4	0.26
17:00	460.3	26.1	0.12
17:00-9:00	-	-	0.17
Ave	715.3	28.02	-
			Tot = 2.25 Lit/m^2.day

TableA.6 .Measured Values of October (Type 2):

Time	Radiation W/m^2	T_{amb} ^{o}C	Water Production Lit/m^2
9:00	609.5	26.3	-
10:00	730.1	27.8	0.2
11:00	847.5	28.8	0.27
12:00	869.8	30.3	0.41
13:00	885.6	30.8	0.48
14:00	853.9	29.8	0.47
15:00	752.3	28.8	0.39
16:00	673	28.2	0.37
17:00	555.5	27.2	0.32
17:00-9:00	-	-	0.26
Ave	753.02	28.66	-
			Tot = 3.17 Lit/m^2.day

Table A.7 .Measured Values of October (Type 3):

Time	**Radiation** W/m^2	T_{amb} ^oC	**Water Production** Lit/m^2
9:00	555.5	24.8	-
10:00	679.3	26.4	0.28
11:00	796.8	28.1	0.3
12:00	850.7	29.5	0.47
13:00	863.4	29.9	0.52
14:00	838.1	28.9	0.49
15:00	736.5	27.6	0.46
16:00	647.6	26.8	0.41
17:00	571.4	25.5	0.39
17:00-9:00	-	-	0.37
Ave	726.58	27.5	-
			Tot = 3.69 $Lit/m^2.day$

Table A.8 .Measured Values of October (Type 4):

Time	**Radiation** W/m^2	T_{amb} ^oC	**Water Production** Lit/m^2
9:00	631.7	24.3	-
10:00	707.9	25.5	0.31
11:00	841.2	26.7	0.35
12:00	873	29	0.5
13:00	847.5	29.5	0.53
14:00	825.3	28.8	0.52
15:00	692.1	27.3	0.49
16:00	603.1	26.5	0.45
17:00	485.7	25.2	0.43
17:00-9:00	-	-	0.47
Ave	723.05	26.97	-
			Tot = 4.05 $Lit/m^2.day$

Table A.9.Measured Values of November (Type1):

Time	**Radiation** W/m^2	**T_{amb}** ^{o}C	**Water production** Lit/m^2
8:00	590.4	22	-
9:00	641.2	23.4	0.08
10:00	746	25.5	0.12
11:00	860.3	26.7	0.22
12:00	882.5	27.6	0.26
13:00	825.3	26.8	0.28
14:00	720.6	25.8	0.25
15:00	654	24.6	0.18
16:00	476.1	24.1	0.13
16:00-8:00	-	-	0.13
Ave	710.71	25.16	-
			Tot = 1.65 Lit/m^2.day

Table A.10. Measured Values of November (Type2):

Time	**Radiation** W/m^2	**T_{amb}** ^{o}C	**Water production** Lit/m^2
8:00	542.8	21.2	-
9:00	609.5	22	0.12
10:00	784.1	23.1	0.23
11:00	844.4	25.2	0.28
12:00	793.6	26.5	0.34
13:00	717.5	26.2	0.37
14:00	698.4	25.3	0.34
15:00	587.3	24.3	0.27
16:00	450.7	23.5	0.17
16:00-8:00	-	-	0.16
Ave	669.81	24.14	-
			Tot = 2.28 Lit/m^2.day

Table A.11. Measured Values of November (Type3):

Time	Radiation W/m^2	T_{amb} ^{o}C	Water production Lit/m^2
8:00	536.5	20.8	-
9:00	606.3	21	0.14
10:00	692.1	23	0.23
11:00	857.1	24.1	0.27
12:00	796.5	26.1	0.34
13:00	692.4	26.2	0.38
14:00	520.6	25	0.35
15:00	473	24.1	0.3
16:00	409.5	22.8	0.26
16:00-8:00	-	-	0.27
Ave	620.44	23.67	-
			Tot = 2.54 Lit/m^2.day

Table A.12. Measured Values of November (Type4):

Time	Radiation W/m^2	T_{amb} ^{o}C	Water production Lit/m^2
8:00	584.1	20.5	-
9:00	695.3	22	0.14
10:00	793.6	23.6	0.22
11:00	841.2	24.3	0.29
12:00	838	26.2	0.43
13:00	742.8	25	0.47
14:00	654	24.1	0.43
15:00	527	23.6	0.37
16:00	447.5	22.9	0.29
16:00-8:00	-	-	0.28
Ave	680.38	23.57	-
			Tot = 2.92 Lit/m^2.day

Table A.13. Measured Values of March (Type1):

Time	**Radiation** **W/m^2**	**T_{amb}** **^oC**	**Water production** **Lit/m^2**
8:00	487.3	19.2	-
9:00	506.8	20.2	0.07
10:00	622.2	22.5	0.13
11:00	744.9	23.5	0.23
12:00	850.7	25.2	0.27
13:00	812.5	24.7	0.26
14:00	755.5	23.8	0.17
15:00	625.3	22.6	0.15
16:00	506.8	21.5	0.12
16:00-8:00	-	-	0.16
Ave	656.88	22.57	-
			Tot = 1.56 Lit/m^2.day

Table A.14. Measured Values of March (Type2):

Time	**Radiation** **W/m^2**	**T_{amb}** **^oC**	**Water production** **Lit/m^2**
8:00	498.3	18.5	-
9:00	614.7	19.8	0.17
10:00	725.2	22.1	0.2
11:00	783.4	23.1	0.31
12:00	868.3	24.3	0.34
13:00	850.3	24.1	0.31
14:00	754.6	23.2	0.29
15:00	621.4	22.1	0.22
16:00	488.6	20.2	0.17
16:00-8:00	-	-	0.15
Ave	689.42	21.93	-
			Tot = 2.16 Lit/m^2.day

Table A.15. Measured Values of March (Type3):

Time	Radiation W/m^2	T_{amb} ^oC	Water production Lit/m^2
8:00	497.3	19	-
9:00	585.4	21	0.15
10:00	697.5	23.1	0.21
11:00	839.2	24.2	0.32
12:00	885.9	25.1	0.36
13:00	840.2	24.4	0.34
14:00	724.9	23.2	0.31
15:00	650.1	22.1	0.26
16:00	548.3	21	0.22
16:00-8:00	-	-	0.26
Ave	696.53	22.56	-
			Tot = 2.43 Lit/m^2.day

Table A.16. Measured Values of March (Type4):

Time	Radiation W/m^2	T_{amb} ^oC	Water production Lit/m^2
8:00	459.3	18.9	-
9:00	592.5	20.9	0.17
10:00	694.6	22.1	0.22
11:00	792.5	23.2	0.38
12:00	851.3	24.8	0.46
13:00	812.4	24.1	0.39
14:00	698.7	23.2	0.36
15:00	583.4	22.5	0.28
16:00	478.3	20.8	0.22
16:00-8:00	-	-	0.23
Ave	662.55	22.27	-
			Tot = 2.71 Lit/m^2.day

Table A.17. Measured Values of April (Type1):

Time	Radiation W/m^2	T_{amb} °C	Water production Lit/m^2
9:00	515.3	26.2	-
10:00	603.5	27.4	0.21
11:00	716.3	28.5	0.25
12:00	802.5	29.9	0.31
13:00	862.3	31	0.37
14:00	843.3	30.1	0.46
15:00	740.5	29.3	0.39
16:00	645.3	28.1	0.3
17:00	517.8	27.4	0.23
17:00-9:00	-	-	0.28
Ave	694.08	28.65	-
			Tot = 2.80 Lit/m^2.day

Table A.18.Measured Values of April (Type2):

Time	Radiation W/m^2	T_{amb} °C	Water production Lit/m^2
9:00	531.7	25.3	-
10:00	716.8	26.8	0.27
11:00	792.4	28.5	0.32
12:00	875.6	30.1	0.41
13:00	899.8	31.2	0.52
14:00	824.3	30.3	0.56
15:00	683.6	29.4	0.52
16:00	593.8	27.8	0.4
17:00	527.7	26.5	0.25
17:00-9:00	-	-	0.55
Ave	716.18	28.43	-
			Tot = 3.8 Lit/m^2.day

Table A.19. Measured Values of April (Type3):

Time	Radiation W/m²	T_{amb} ^{o}C	Water production Lit/m²
9:00	499.8	25.8	-
10:00	582.3	26.8	0.3
11:00	725.8	27.2	0.43
12:00	783.9	28.5	0.46
13:00	877.4	30.8	0.61
14:00	856.8	30.1	0.66
15:00	830.8	29.2	0.59
16:00	693.5	27.8	0.45
17:00	572.3	26.3	0.41
17:00-9:00	-	-	0.56
Ave	713.62	28.05	-
			Tot = 4.47 $Lit/m^2.day$

Table A.20.Measured Values of April (Type4):

Time	Radiation W/m²	T_{amb} ^{o}C	Water production Lit/m²
9:00	515.8	26.2	-
10:00	608.5	27.1	0.38
11:00	698.3	28.4	0.48
12:00	851.4	29.3	0.57
13:00	861.4	30.7	0.64
14:00	795.6	30.5	0.67
15:00	708.9	28.7	0.57
16:00	621.4	27.1	0.49
17:00	554.3	26.2	0.41
17:00-9:00	-	-	0.65
Ave	690.62	28.24	-
			Tot = 4.86 $Lit/m^2.day$

Table A.21. Measured Values of May (Type1):

Time	**Radiation** **W/m^2**	**T_{amb}** **^oC**	**Water production** **Lit/m^2**
9:00	514.3	25.4	-
10:00	581	26.2	0.26
11:00	752.4	27.3	0.32
12:00	885.7	29.4	0.37
13:00	914.3	31.3	0.44
14:00	885.7	30.2	0.5
15:00	780.9	29.2	0.45
16:00	619	28.3	0.37
17:00	504.7	27.3	0.28
17:00-9:00	-	-	0.34
Ave	715.33	28.28	-
			Tot = 3.33 Lit/m^2.day

Table A.22. Measured Values of May (Type2):

Time	**Radiation** **W/m^2**	**T_{amb}** **^oC**	**Water production** **Lit/m^2**
9:00	524.9	25.2	-
10:00	595.3	26.3	0.3
11:00	698.4	27.8	0.36
12:00	840.2	29.8	0.49
13:00	885.7	31.2	0.56
14:00	847.7	31	0.62
15:00	764.8	29.3	0.58
16:00	592.5	28.6	0.46
17:00	487.6	26.9	0.34
17:00-9:00	-	-	0.58
Ave	693.01	28.45	-
			Tot = 4.29 Lit/m^2.day

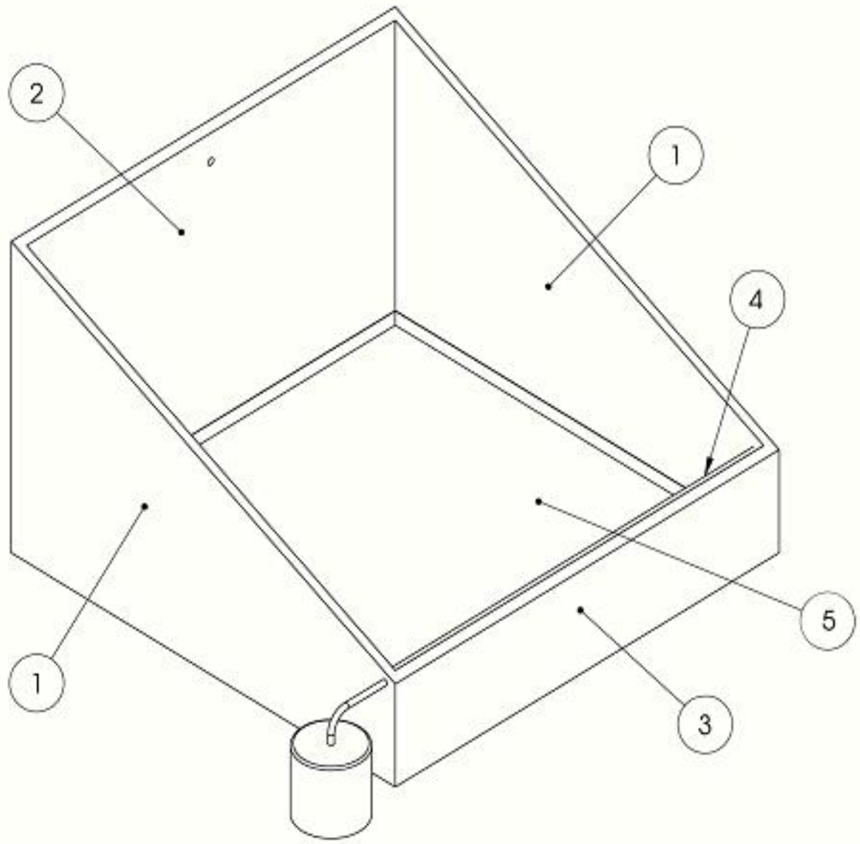
Table A.23. Measured Values of May (Type3):

Time	**Radiation** W/m^2	T_{amb} ^oC	**Water production** Lit/m^2
9:00	508.4	26.5	-
10:00	708.2	27.3	0.35
11:00	821.3	28.9	0.45
12:00	879.3	30.3	0.49
13:00	931.4	32.3	0.64
14:00	868.5	31.2	0.68
15:00	793.2	29.8	0.62
16:00	725.8	28.7	0.48
17:00	582.3	27.4	0.45
17:00-9:00	-	-	0.68
Ave	757.6	29.15	-
			Tot = 4.84 $Lit/m^2.day$

Table A.24. Measured Values of May (Type4):

Time	**Radiation** W/m^2	T_{amb} ^oC	**Water production** Lit/m^2
9:00	535.7	25.3	-
10:00	716.3	26.5	0.45
11:00	793.5	28.4	0.54
12:00	863.5	29.7	0.63
13:00	908.2	31.2	0.7
14:00	891.6	30.1	0.73
15:00	825.4	29.2	0.58
16:00	719.3	28.3	0.57
17:00	559.8	26.9	0.5
17:00-9:00	-	-	0.67
Ave	757.03	28.4	-
			Tot = 5.37 $Lit/m^2.day$

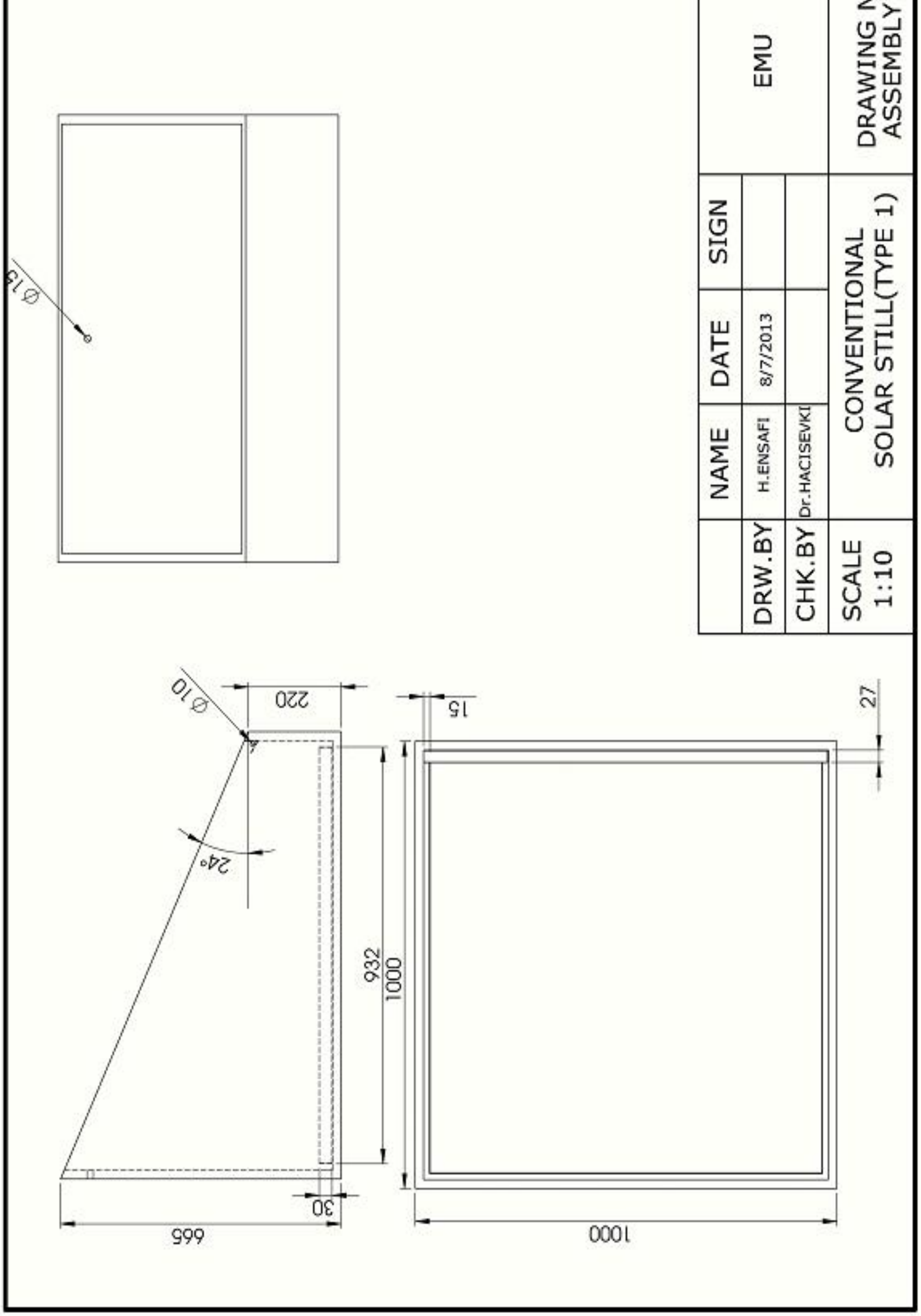
In the following, there are technical drawings of each model of this experimental study (Type1-Type4).



ITEM NO.	PART NUMBER	MATERIAL	QTY.
5	PART 5	GALVANIZED IRON	1
4	PART 4	GALVANIZED IRON	1
3	PART 3	WOOD	1
2	PART 2	WOOD	1
1	PART 1	WOOD	2

	NAME	DATE	SIGN	
DRW.BY	H.ENSAFI	8/7/2013		EMU
CHK.BY	Dr.HACISEVKI			

SCALE 1:10	CONVENTIONAL SOLAR STILL(TYPE 1)	DRAWING NO ASSEMBLY 1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ASSEMBLY
NAME
DATE
SIGN
DRW.BY
H.ENSAFI
8/7/2013
CHK.BY
Dr.HACISEVKI
SCALE
1:10
CONVENTIONAL
SOLAR STILL(TYPE 1)
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Ø10
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24°
932
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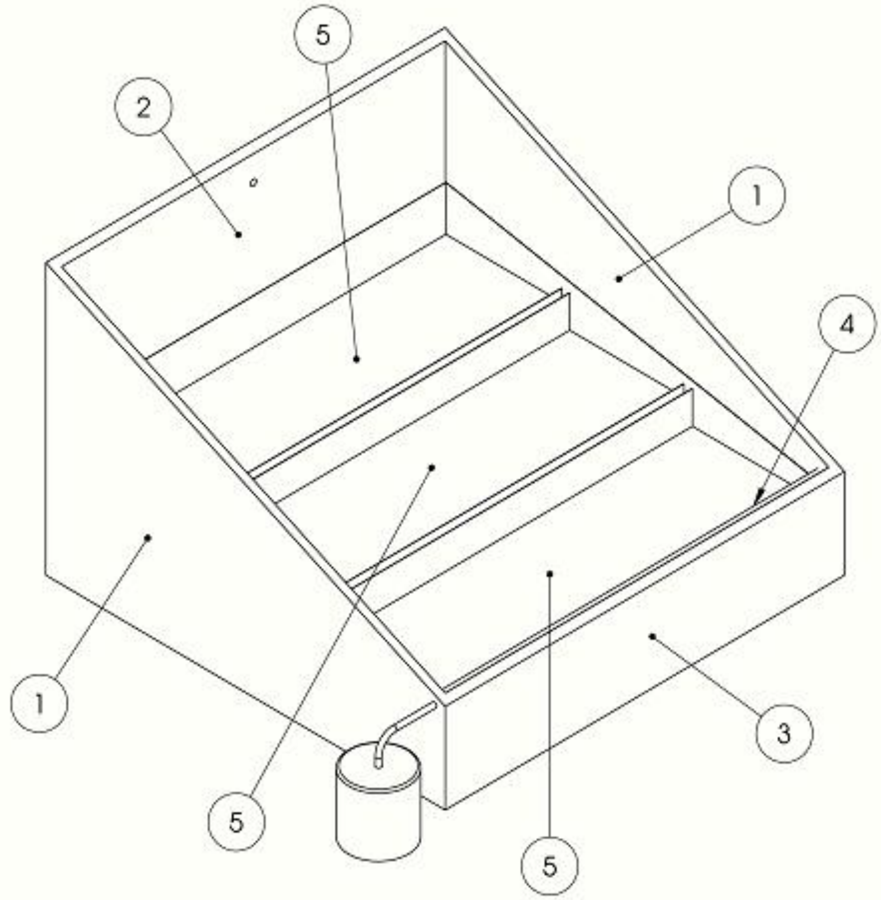
27
30
665
1000



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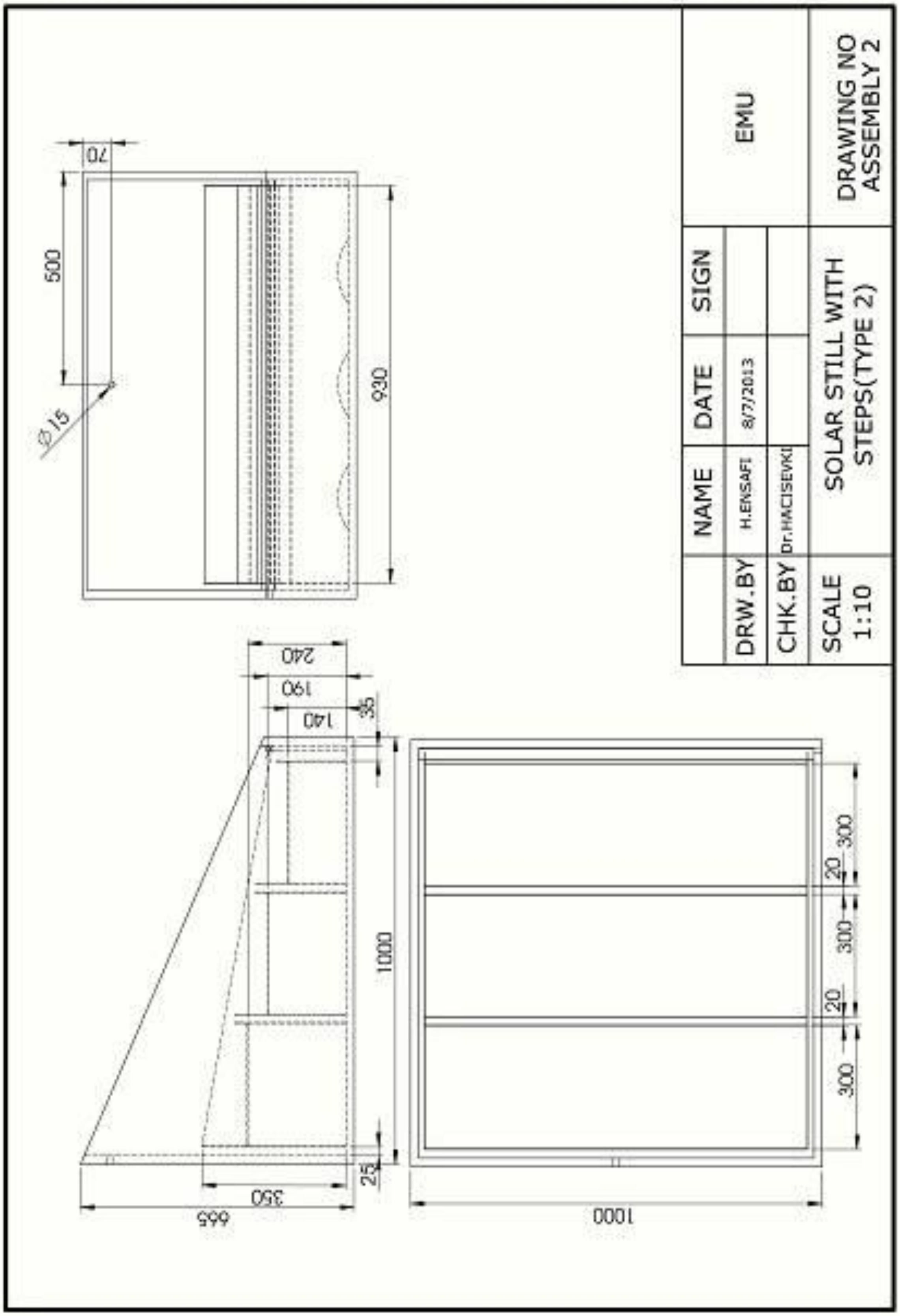
4	PART 4	GALVANIZED IRON	1
3	PART 3	WOOD	1
2	PART 2	WOOD	1
1	PART 1	WOOD	2

	NAME	DATE	SIGN	
DRW.BY	H.ENSAFI	8/7/2013		EMU
CHK.BY	Dr.HACISEVKI			
SCALE 1:10	SOLAR STILL WITH STEPS(TYPE 2)			DRAWING NO ASSEMBLY 2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DRAWING NO
ASSEMBLY 2
NAME
DATE
SIGN
DRW.BY
H.ENSAFI
8/7/2013
CHK.BY
Dr.HACISEVKI
SCALE
1:10
SOLAR STILL WITH
STEPS(TYPE 2)
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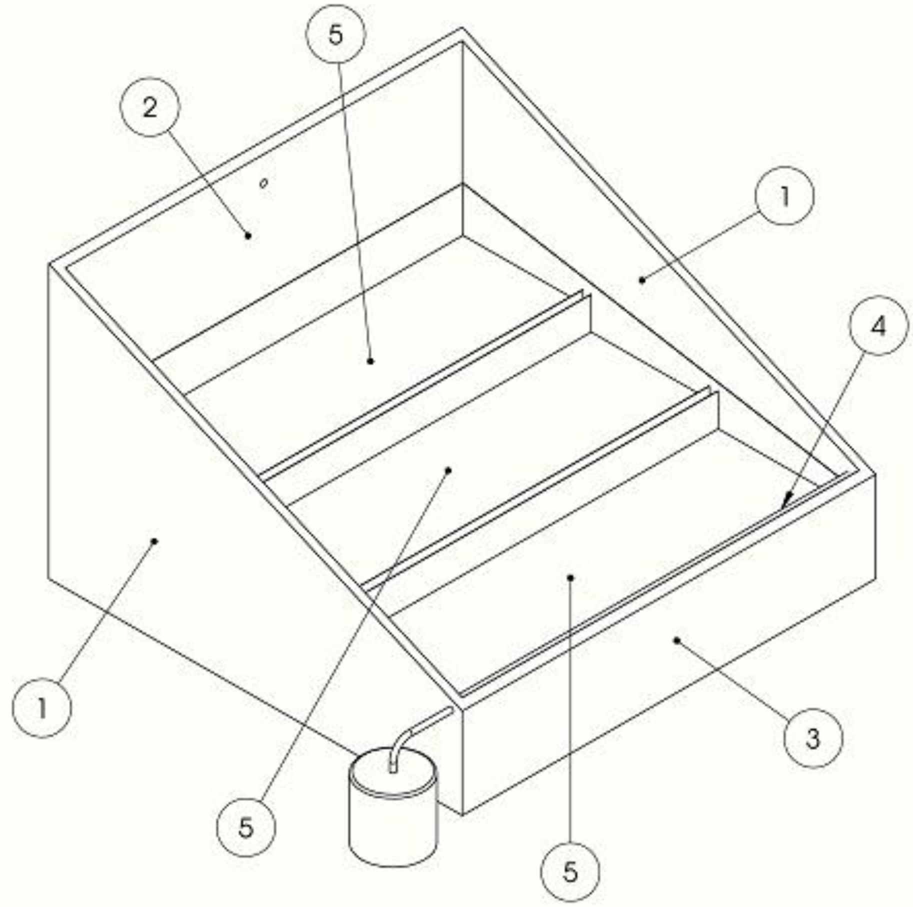
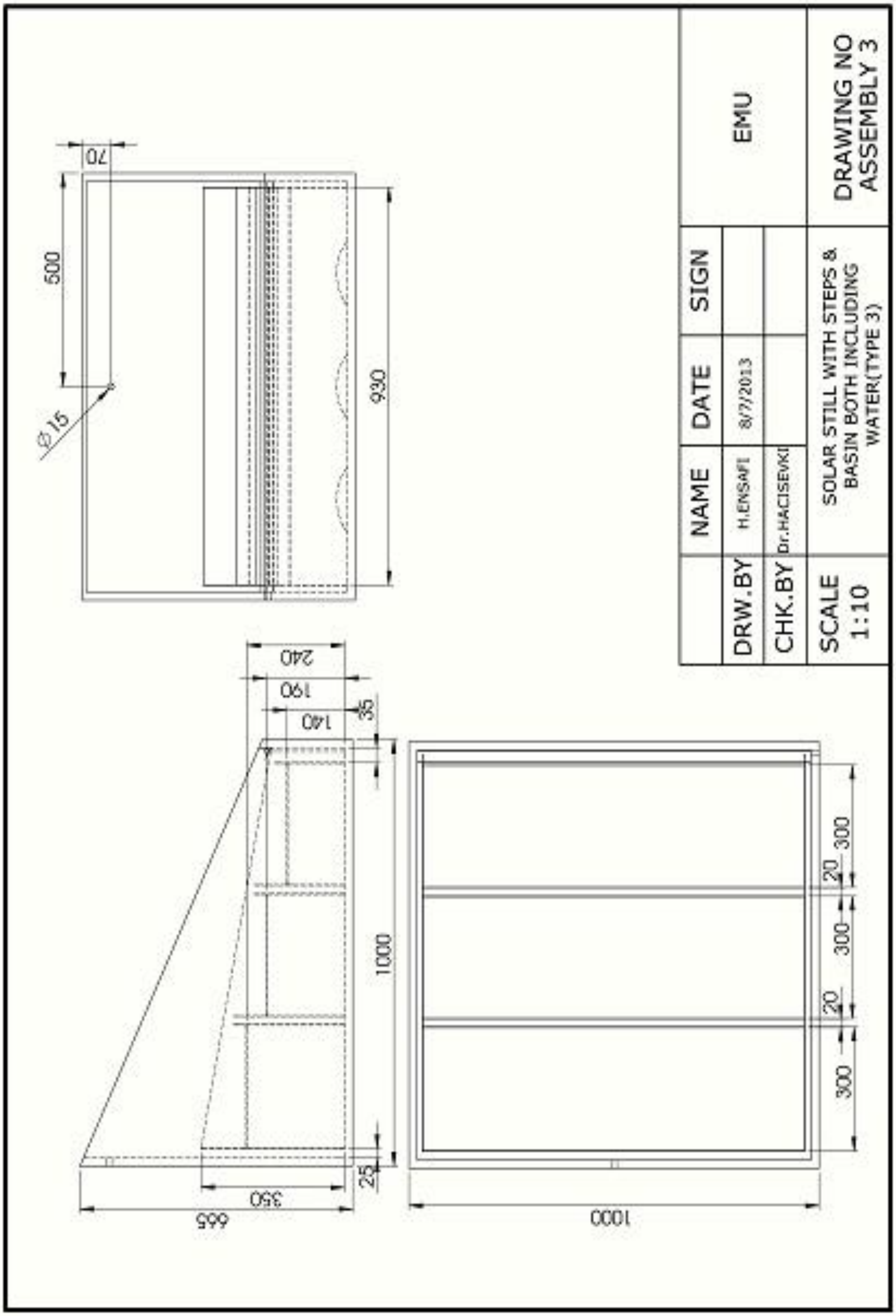
70
930
1000
665
350
25
35
140
190
240
300
20
300
20
300
1000



ITEM NO.	PART NUMBER	MATERIAL	QTY.
6	PART 6	GALVANIZED IRON	1
5	PART 5	GALVANIZED IRON	3
4	PART 4	GALVANIZED IRON	1
3	PART 3	WOOD	1
2	PART 2	WOOD	1
1	PART 1	WOOD	2

	NAME	DATE	SIGN	
DRW.BY	H.ENSAFI	8/7/2013		EMU
CHK.BY	Dr.HACISEVKI			
SCALE 1:10	SOLAR STILL WITH STEPS & BASIN BOTH INCLUDING WATER(TYPE 3)			DRAWING NO ASSEMBLY 3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DRAWING NO
ASSEMBLY 3
NAME
DATE
SIGN
DRW.BY
H.ENSAFI
8/7/2013
CHK.BY
Dr.HACISEVKI
SCALE
1:10
SOLAR STILL WITH STEPS &
BASIN BOTH INCLUDING
WATER(TYPE 3)
500
70
Ø15
930
240
190
140
35
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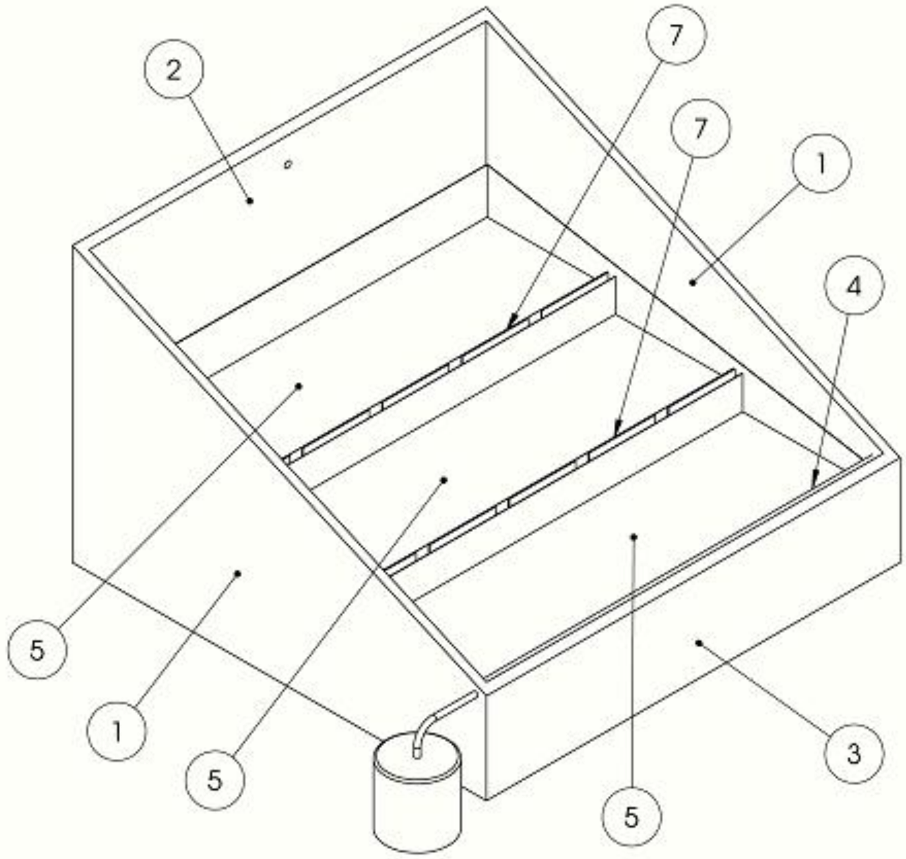
25
350
665
1000
300
20
300
20
300



ITEM NO.	PART NUMBER	MATERIAL	QTY.
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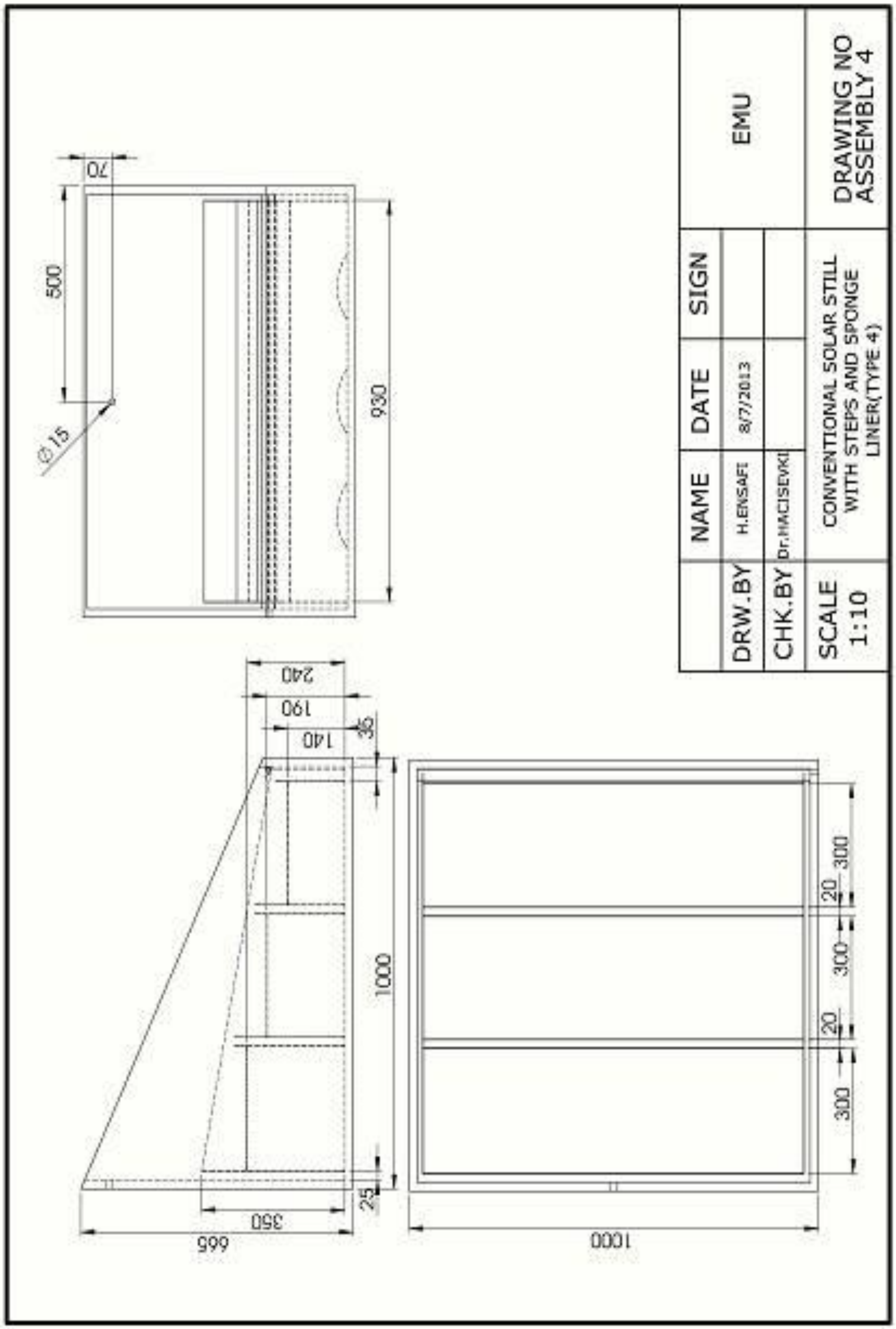
6	PART 6	GALVANIZED IRON	1
5	PART 5	GALVANIZED IRON	3
4	PART 4	GALVANIZED IRON	1
3	PART 3	WOOD	1
2	PART 2	WOOD	1
1	PART 1	WOOD	2

	NAME	DATE	SIGN	
DRW.BY	H.ENSAFI	8/7/2013		EMU
CHK.BY	Dr.HACISEVKI			
SCALE 1:10	CONVENTIONAL SOLAR STILL WITH STEPS AND SPONGE LINER(TYPE 4)			DRAWING NO ASSEMBLY 4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DRAWING NO
ASSEMBLY 4
NAME
DATE
SIGN
DRW.BY
H.ENSAFI
8/7/2013
CHK.BY
Dr.HACISEVKI
SCALE
1:10
CONVENTIONAL SOLAR STILL
WITH STEPS AND SPONGE
LINER(TYPE 4)
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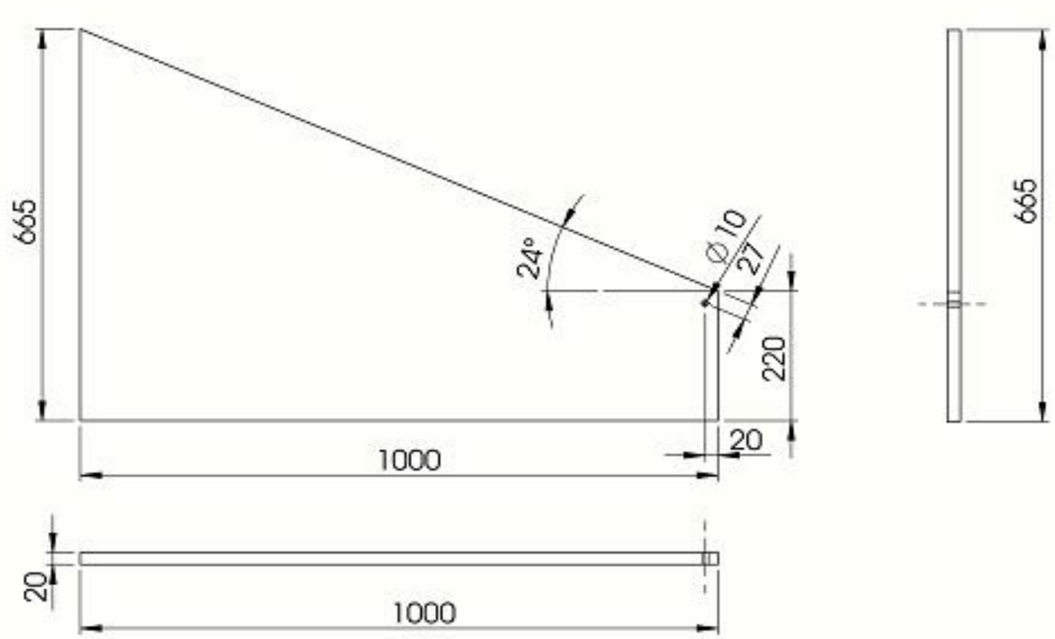
500
Ø15
930
240
190
140
35
1000
300
20
300
20
300
25
350
665
1000



	NAME	DATE	SIGN	EMU
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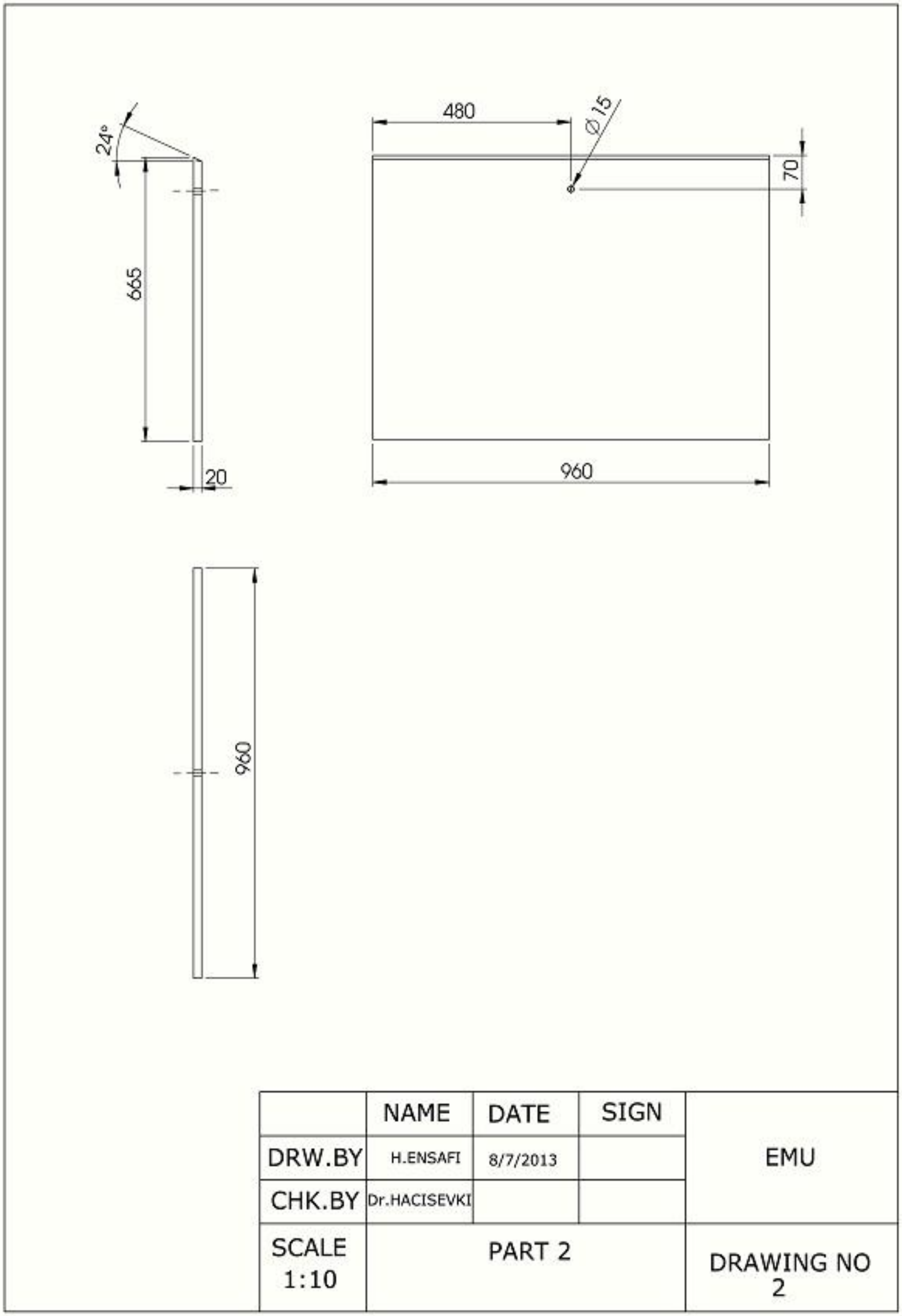
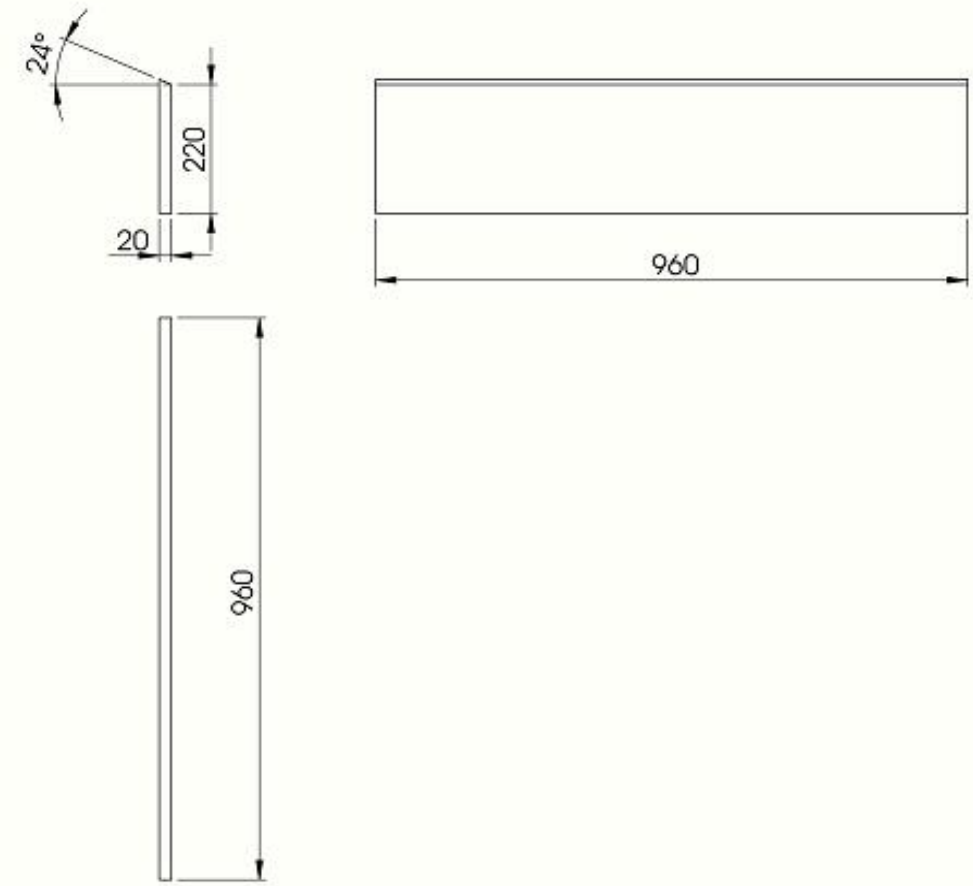
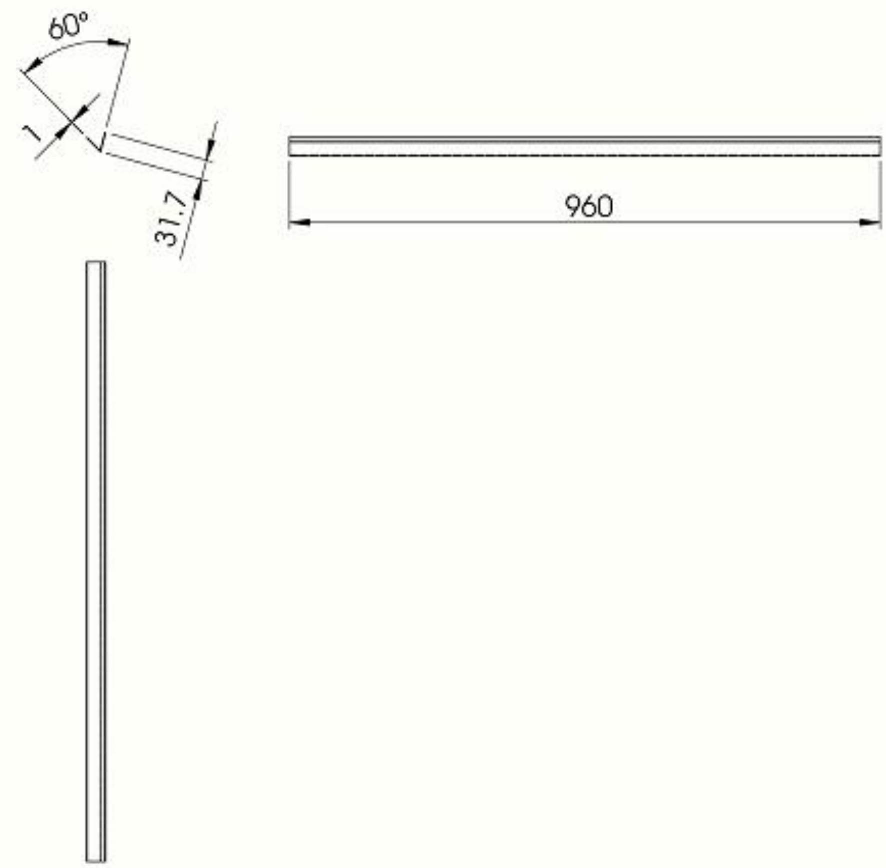
CHK.BY	Dr.HACISEVKI			
SCALE 1:10	PART 1			DRAWING NO 1

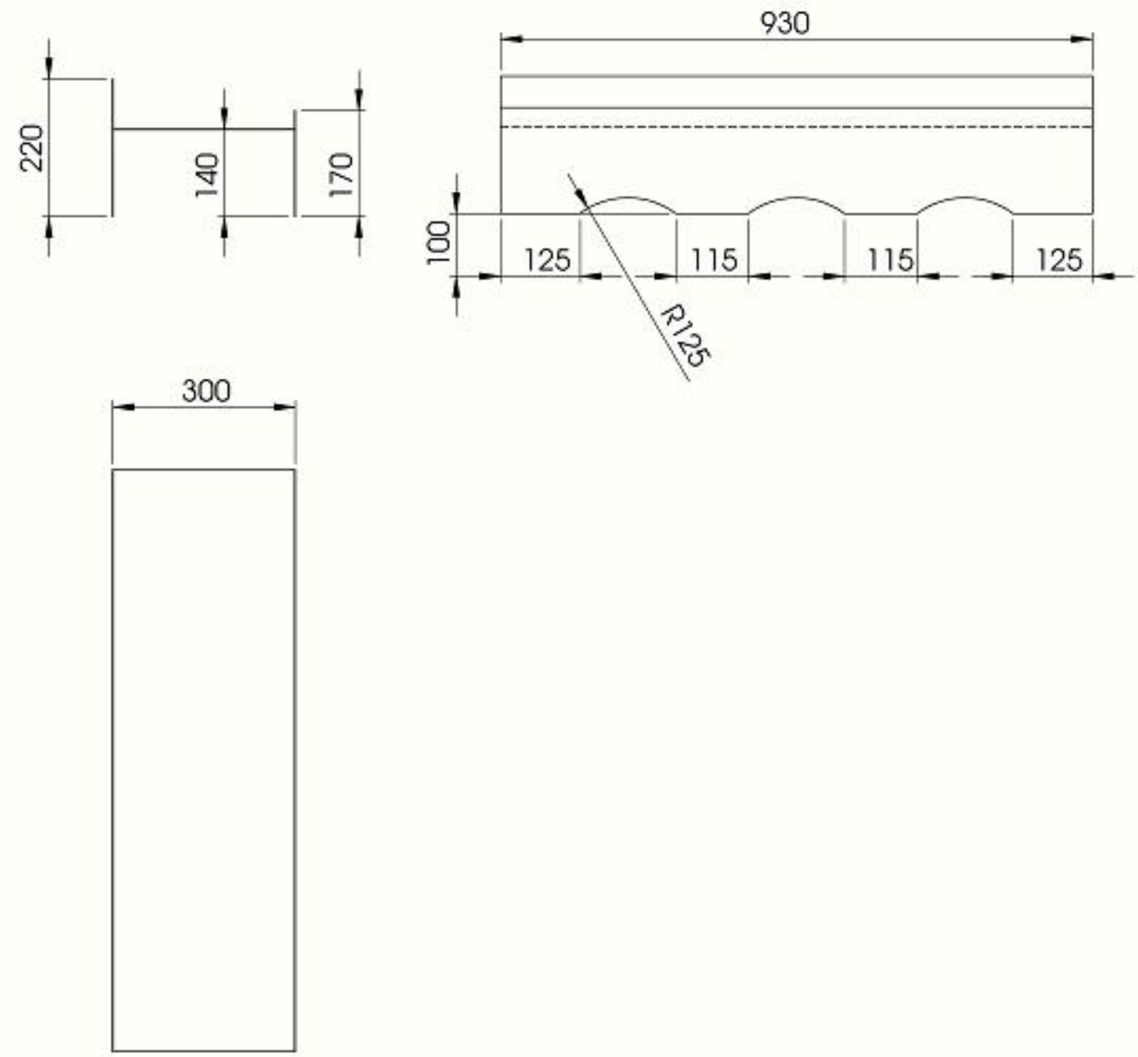

24°
665
20
480
Ø15
70
960
960
NAME
DATE
SIGN
DRW.BY
H.ENSAFI
8/7/2013
CHK.BY
Dr.HACISEVKI
EMU
SCALE
1:10
PART 2
DRAWING NO
2



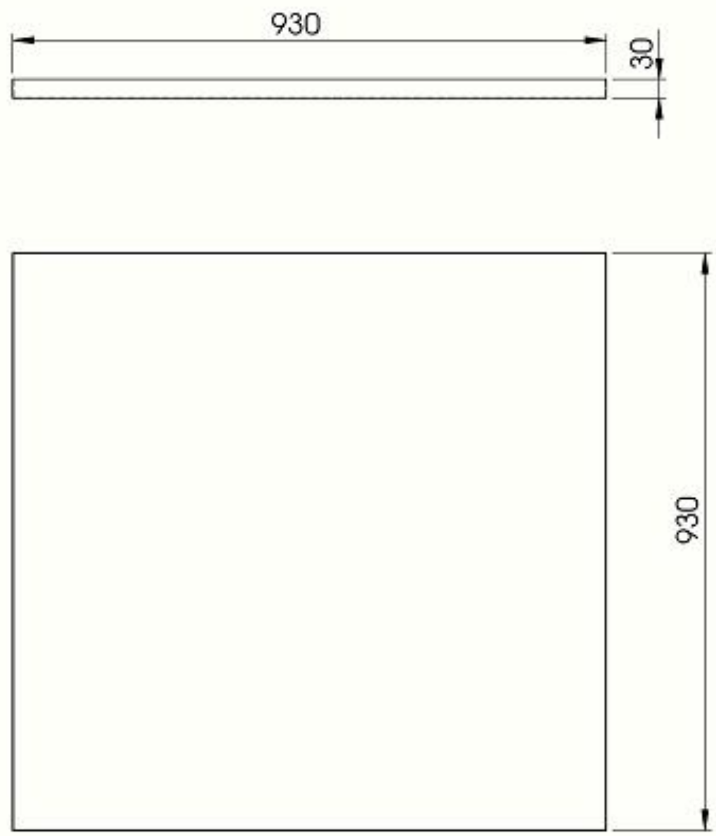
	NAME	DATE	SIGN	
DRW.BY	H.ENSAFI	8/7/2013		EMU
CHK.BY	Dr.HACISEVKI			
SCALE 1:10	PART 3			DRAWING NO 3



	NAME	DATE	SIGN	EMU
DRW.BY	H.ENSAFI	8/7/2013		
CHK.BY	Dr.HACISEVKI			
SCALE 1:10	PART 4			DRAWING NO 4



	NAME	DATE	SIGN	
DRW.BY	H.ENSAFI	8/7/2013		EMU
CHK.BY	Dr.HACISEVKI			
SCALE 1:10	PART 5			DRAWING NO 5



	NAME	DATE	SIGN	
DRW.BY	H.ENSAFI	8/7/2013		EMU
CHK.BY	Dr.HACISEVKI			
SCALE 1:10	PART 5 ASSEMBLY 1			DRAWING NO 5