THE UNIVERSITY OF ZAMBIA

SCHOOL OF ENGINEERING

DEPARTMENT OF AGRICULTURAL ENGINEERING

PERFORMANCE IMPROVEMENT OF A SOLAR WATER STILL BY USING REFLECTORS

BY

HUMPHREY MAAMBO

2015

The University of Zambia

School of Engineering

Department of Agricultural Engineering

Performance improvement of a solar water still by using reflectors

By

Humphrey Maambo

Supervisor: Dr. I.N. Simate

"Report submitted in partial fulfilment of the requirements for the degree of Bachelor of engineering, University of Zambia"

June 2015

ACKNOWLEDGEMENTS

I take this momentous opportunity to express my heartfelt gratitude and regards to my highly esteemed guide, Dr. I.N. Simate, Lecturer, Department of Agricultural Engineering, for giving me an opportunity to do this project under his supervision.

I would also like to thank Zambia Sugar Plc., my sponsors, for their financial support. In addition, I would also like to thank all the staff in the Department of Agricultural Engineering for invaluable advice and wholehearted cooperation without which this project would not have been as successful as it turned out to be.

Lastly, my appreciation goes to my family and friends for their encouragement and moral support towards my project.

Table of Contents

Acknowledgements i

Table of contents ii

List of figures iv

Nomenclature v

Abstract viii

CHAPTER 1 1

1 INTRODUCTION 1

1.1 PROJECT OVERVIEW 1

1.2 PROBLEM STATEMENT 7

1.3 RATIONALE 8

1.4 OBJECTIVES 8

CHAPTER 2 9

2 REVIEW OF LITERATURE 9

2.1 HISTORICAL BACKGROUND 9

2.2 SOLAR DISTILLATION 9

2.3 NEEDS SERVED BY SOLAR DISTILLATION 11

2.4 OPERATING PRINCIPLES 13

2.5 COMPARATIVE ADVANTAGE 13

2.6 MARKET POTENTIAL 16

2.7 CHOOSING THE TECHNOLOGY RIGHT FOR YOU 16

2.8 OPERATION AND MAINTENANCE OF SOLAR STILL 17

2.9 FACTORS INFLUENCING SOLAR STILL OPERATING PERFORMANCE 18

2.10 MAINTENANCE REQUIREMENTS OF BASIN STILLS 20

CHAPTER 3 22

3 METHODOLOGY 22

3.1 DESIGN 22

3.2 THEORETICAL ANALYSIS 24

3.3 APPROACHES TO ACHIEVING OBJECTIVES 33

CHAPTER 4 34

4 RESULTS AND DISCUSSION 34

4.1 EXPERIMENTAL FINDINGS 34

4.2 THEORETICAL AND EXPERIMENTAL RESULT COMPARISONS 38
4.3 JUSTIFICATION OF USING REFLECTORS 39
CHAPTER 5 40
5 CONCLUSIONS 40
5.1 RECOMMENDATIONS 40
BIBLIOGRAPHY 42
APPENDICES 44

LIST OF FIGURES

FIGURE PAGE

Figure 1. Solar distillation process …………………………………………………….... 13

Figure 2. Solar still with reflectors …………………………………………………..… 14

Figure 3. Optimum reflector angle …………………………………………………..… 19

Figure 4. Penetration percentage with varying angles ……………………………...… 19

Figure 5. Schematic diagram of still showing equation descriptions ……………………... 24

Figure 6. Energy flow of solar still ………...…….……………………….…….……….…….… 26

Figure 7. Radiation at solar noon with 150 mm reflectors at 120˚ …………………………. 31

Figure 8. Radiation at solar noon with 150 mm reflectors at 150˚ …………………………. 31

Figure 9. Radiation at solar noon with 150 mm reflectors at 90˚ ……………………...… 32

Figure 10. Radiation at solar noon with 200 mm reflectors at 120˚ …………..…….……… 32

Figure 11. Radiation at solar noon with 75 mm reflectors at 120˚ …………………….……… 32

Figure 12. Histogram of solar still distillate output per experiment ...………………...…… 34

Figure 13: Graph of distillate output vs temperature (without reflectors) …..………...…… 37

Figure 14: Graph of distillate output vs temperature (with reflectors) …………….……… 37

Figure 15: Design front view ………...…….……………………….…….……….…….… 44

Figure 16: Design top view ………...…….………………...….……….…….……….…….… 45

Figure 17: Design isometric view ….…….……………...….…………….…….……….…….… 45

Figure 18: Design left side view ….…….……..………...….……….…….……….…….… 46

Figure 19: Design right side view ….……...………….…...….……….…….……….…….… 46

Figure 20: Design still basin left side view …….………..….……….…….……….…….… 47

Figure 21: Design still basin front view …….…………...….……….…….……….…….… 47

Figure 22: Design 3D front view …….……………….…….……….…….……….…….….… 48

Figure 23: Fabricated design front view …….…………….…….……….…….……….….… 48

Figure 24: Weighing of distilled water sample …….……...….……….…….……….…..… 49

Figure 25: Water quality testing …….….…………………..…….……….…….……….….… 49

NOMENCLATURE

α_g Solar flux received from sun, W/m^2

α_g' Solar flux absorbed by glass, W/m^2

R_g Solar flux reflected by glass, W/m^2

R_w' Solar flux reflected by the water mass, W/m^2

R_w Solar flux received by the water mass, W/m^2

A_w' Solar flux absorbed by the water mass, W/m^2

α_w' Solar flux received inside the basin, W/m^2

α_w Solar flux received by the water mass, W/m^2

α_b Solar flux received by basin liner, W/m^2

α_b' Solar flux absorbed by basin liner, W/m^2

L_a' Solar flux lost by the ambient, W/m^2

$I(t)$ Amount of solar radiation within a given time interval, W/m^2 s

A_s Area of still, m^2

Q_{ew} Heat utilized by still, J

Q_{losses} Heat losses from still, J

m_w Daily output of the distillate, Kg

L Latent heat of vaporization, J/Kg

U_L' Overall heat transfer coefficient, W/m^2 ˚C

T_w Temperature of water inside still, ˚C

T_a Ambient temperature, ˚C

$(\alpha\tau)_w$ Transmittance-absorptance product

q_g Total external heat transfer losses from glass, W

q_{rg} Radiation heat transfer losses from glass, W

q_{cg} Convection heat transfer losses from glass, W

ε_g Emissivity of glass cover

σ Stefan – Boltzmann constant, $5.67x10^{-8}$ W/m^2 ˚K

T_g Glass temperature, ˚K

T_s Sky temperature, ˚K

h_{cg} Forced convective heat transfer coefficient from glass, W/m^2 ˚K

h_{rg} Forced radiative heat transfer coefficient from glass, W/m^2 ˚K

v Wind speed, m/s

U_b Bottom loss coefficient, W/m^2 ˚K

h_w Convective heat transfer coefficient from water, W/m^2 ˚K

h_b Radiative heat transfer coefficient from bottom, W/m^2 ˚K

k_i Thermal conductivity of air, W/m ˚K

L_i Insulation thickness, m

h_{cb} Forced convective heat transfer coefficient from water to bottom, W/m^2 ˚K

h_{rb} Forced radiative heat transfer coefficient from water to bottom, W/m^2 ˚K

U_s Side heat loss coefficient, W/m^2 ˚K

A_{ss} Surface area in contact with water, m^2

q_b Rate of heat loss from basin liner to ambient, W

T_b Basin liner temperature, ˚K

q_{rw} Radiation heat transfer losses from water, W

q_{cw} Convection heat transfer losses from water, W

h_{rw} Forced radiative heat transfer coefficient from water to glass, W/m^2 ˚K

h_{cw} Forced convective heat transfer coefficient from water to glass, W/m^2 ˚K

P_w Saturation partial pressures of water at water temperature, Pa

P_g Saturation partial pressures of water at glass temperature, Pa

h_e Mass transfer coefficient, m/s

M_w Mass of water vapour, Kg

M_a Mass of air, Kg

C_{pa} Specific heat at constant pressure, J/Kg ˚K

P_T Total gas pressure, Pa

$P(T)$ Saturated vapour pressure, Pa

m_{ew} Hourly distillate yield, Kg

η_i Instantaneous efficiency of the still unit

α_a Absorptivity

ρ Reflectivity

τ_t Transmissivity

λ Wavelength, m

n Refractive index

k Extinction coefficient of the material, m^{-1}

τ_α Absorption losses

θ_1 Incidence angle

θ_2 Refracted to angle

I Intensity, $\mathrm{W/m}^2$

l Glass thickness, m

mm Millimeter

cm Centimeter

˚K Degrees Kelvin

˚C Degrees Celsius

Abstract

Water is a basic need for human beings along with food and air. The increasing demand for potable water represents one of the best applications of solar energy. The supply of drinking and agricultural water has become a major problem in many third world countries, and is one of the most important challenges man has in order to speed up growth, development, and the quality of life for the populations in these countries. Solar water distillation represents an important alternative to palliate the problem of fresh water shortages. Various designs of solar stills have been constructed and efforts have been devoted to increase their overall efficiency. Only a small percentage increase in efficiency has been achieved in most cases. Economic analyses performed have shown that distilled water production for potable use may be 3-5 times more economical than commercial water acquisition. Therefore there is need to improve solar still performance.

CHAPTER 1

1 INTRODUCTION

1.1 PROJECT OVERVIEW

1.1.1 Introduction

Water is the basic necessity for humans along with food and air. There is almost no water left on Earth that is safe to drink without purification. Only 1% of Earth's water is in a fresh, liquid state, and nearly all of this is polluted by both disease causing pathogens and toxic chemicals (El-Sabaii, 2009). For this reason, purification of water supplies is extremely important.

Moreover, typical purification systems are easily damaged or compromised by disasters, natural or otherwise. This results in a very challenging situation for individuals trying to prepare for such situations, and keep themselves and their families safe from the myriad diseases and toxic chemicals present in untreated water (El-Sabaii, 2009).

Everyone wants to find out the solution to this problem with the available sources of energy in order to achieve pure water. Fortunately there is a solution to these problems. It is a technology that is not only capable of removing a very wide variety of contaminants in just one step, but is simple, cost-effective, and environmentally friendly. That is use of solar energy.

1.1.2 Solar energy potential

Interest in clean and renewable energy sources is growing and will continue to grow as more people recognize that fossil fuels like coal, oil, and natural gas are limited resources and that burning fossil fuels releases large amounts of carbon dioxide, a greenhouse gas, into the Earth's atmosphere. Renewable energy sources are derived from everyday occurrences in the environment, from items that can be re-grown, or from bi-products of human/animal activity. The most prominent and environmentally forms of sustainable energy are captured from natural sources like wind, ocean tides, and sunlight (Chewe, 2013).

Among the many renewable energy alternatives, solar energy remains one of the most well-known and adaptable methods for producing heat and electricity. For smaller, residential scale applications, solar energy is used to heat water or is converted directly to electricity through photovoltaic (PV) solar panels. For larger, utility-scale applications, solar energy can feed vast PV solar panel farms, or be concentrated to vaporize fluids or to run heat engines. Solar energy uses can be diverse if advances could be made in improving energy conversion technologies (Ronnelid, 2000).

Every hour, the sun radiates more energy onto the earth than the entire human population uses in one whole year. The technology required to harness the power of the sun is now available. Solar power alone could provide all of the energy the world consumes. There is no shortage of solar energy. Energy independence could be achieved with solar energy alone. Sunlight has the advantage of zero fuel cost but it requires more space (for its collection) and generally more costly equipment. To dispel a common belief, it is not necessary to boil water to distil it. Simply elevating its temperature, short of boiling, will adequately increase the evaporation rate (Kumar, 2008).

Every square meter of the earth's surface, when exposed to direct sunlight, receives about 1000 watts (1 kilowatt) of energy from the sun's light. Depending on the angle of sunlight, which changes with the time of day, and the geographical location, the power of the sun's light will be somewhat more or less than 1 kilowatt-hour per hour for every square meter of the earth's surface exposed to the sun. However, sunlight will provide useful solar energy for only about 6 to 7 hours per day because during the early hours and late hours of the day the angle of the sun's light is too low. So, for example, if the sun's light provides 6 productive hours of solar energy per day, then a square meter of land in direct sunlight will receive about 6 kilowatt-hours of solar energy during the course of a day (Kumar, 2008).

It would be great if 100% of the sunshine could be converted into another form of energy but conversion techniques experience energy losses. In other words, the new form of energy will be less than the original. Efficiency is the word scientists use to describe the difference in power resulting from the conversion of one form of energy to another. The efficiency of commercially available solar panels (PV) is about 15% (Ronnelid, 2000). This means that when a solar panel converts the sun's light to electricity, only about 15 percent of the energy in the sunlight becomes electricity.

The reason why solar energy has not been development on a large scale is the cost. Not the cost of sunshine, that is free. Private investors resist putting their money into solar energy projects because of the high upfront capital investment required for plant and equipment. The initial investment is what causes the price per kilowatt-hour for electricity from solar energy to be higher than the price of electricity generated from natural gas or coal. The estimated kilowatt-hour rates assigned to solar energy are not based on the cost of electricity generation, they are based on the cost of the investment capital and the requirement to earn a return on investment, or pay back the loan for the investment (Mfune, 2008). Remember, the solar fuel is free. Solar energy would not be expensive if the cost of the initial capital investment is not factored into the price per kilowatt-hour.

174 petawatts (PW) of energy comes in form of solar radiation (or insolation) hits our atmosphere. Almost one third of this is reflected back into space. The rest is absorbed by the atmosphere, clouds, oceans and land. One hour of insolation is the equivalent to more than the world’s energy consumption for an entire year.

$3.8x10^{24}$ joules of solar radiation is absorbed by earth and atmosphere per year. Solar power where sun hits atmosphere is 10^{17} watts and the total demand is 10^{13} watts. Therefore, the sun gives us 1000 times more power than we need. If we can use 5% of this energy, it will be 50 times what the world will require. This makes solar energy is by far the largest energy resource on the Earth (Ronnelid, 2000).

Here are some other interesting comparisons to help make you grasp the massive potential of solar energy:

- ✓ One year's worth of solar energy reaching the surface of the Earth would be twice the amount of all non-renewable resources, including fossil fuels and nuclear uranium.
- ✓ The solar energy that hits the Earth every second is equivalent to 4 trillion 100-watt light bulbs.
- ✓ The solar energy that hits one square mile in a year is equivalent to 4 million barrels of oil (El-Sabaii, 2009).

Unfortunately, far from the entire solar energy potential is exploitable. Solar is an intermittent energy source, which means that it is not available all the time. Sunlight always hits the surface of the Earth, but due to the fact that the Earth rotates about its axis, solar energy is not available on one single location day and night (El-Sabaii, 2009).

Understanding Earth's relationships with the sun leads us directly into a discussion of how the intensity of the sun's rays varies from place to place throughout the year and into an examination of the seasonal changes on Earth. Solar radiation received by the Earth system, known as insolation (for incoming solar radiation), is the main source of energy on our planet (Badran, 2007). The seasonal variations in temperature that we experience are due primarily to fluctuations in insolation.

1.1.3 Water purification

There are four possible ways of purifying water for drinking purpose:

1) Distillation.
2) Filtration.
3) Chemical Treatment.
4) Irradiative Treatment (Christian, 1983).

Considering the areas where the technology is intended to be used we can rule out few of the above mentioned methods based on the unavailability of materials or costs. Chemical treatment is not a stand-alone procedure and so is irradiative treatment. Both can act only remove some specific impurities and hence can only be implemented in coordination with other technologies (Christian, 1983).

This analysis leaves us with two methods; distillation and filtration. By weighting the positive and negatives of both the methods we decided to go by the first one. The most important considerations were that of complexity, higher maintenance and subsequent costs coupled with need of other sophisticated supporting equipment.

Finally we decided to go by distillation method owing to the following benefits:

- ✓ It produces water of high quality.
- ✓ Maintenance is almost negligible.
- ✓ Any type of water can be purified into potable water by means of this process
- ✓ The system will not involve any moving parts and will not require electricity to operate.
- ✓ Wastage of water will be minimal unlike reverse osmosis in which almost 30% of the loaded water flows out in form of unusable water that can only be used for toilet or other cleaning purposes (Christian, 1983).

Sunlight is one of the several forms of heat energy that can be used to power the distillation process. Many levels of purification can be achieved with this process, depending upon the intended application. Sterilized water for medical uses requires a different process than that used to make drinking water. Purification of water heavy in dissolved salts differs from purification of water that has been dirtied by other chemicals or suspended solids (Christian, 1983).

In spite of several technologies, affordable and simple processes have not yet been evolved. In the present work, it is envisaged to improve the absorption of heat from the incident radiation and to hold the energy for sufficiently longer period allowing the system for heat transfer with suitable material. It is also aimed at the development of a collector with suitable heat exchanger. Present work deals with the development of solar collector with good heat absorption and retaining capacity. The cellular material could be developed in the prototype inorganic gel systems. Later it may be extended to the solid and colloidal systems. Solar distillation represents a most attractive and simple technique among other distillation processes and is especially suited to small-scale units at locations where solar energy is ubiquitous (Kumar, 2008).

Solar distillation systems can be small or large. They are designed either to serve the needs of a single family, producing from ½ to 3 gallons of drinking water a day on the average, or to produce much greater amounts for an entire neighbourhood or village. In some parts of the world the scarcity of fresh water is partially overcome by covering shallow salt water basins with glass in greenhouse-like structures. These solar energy distilling plants are relatively inexpensive, low-technology systems, especially useful where the need for small plants exists (Muafag, 2007).

Solar distillation of potable water from saline (salty) water has been practiced for many years in tropical and sub-tropical regions where fresh water is scare. However, where fresh water is plentiful and energy rates are moderate, the most cost-effective method has been to pump and purify.

1.1.4 Need to distillate water

In places like Eastern Africa, native women travel 20 to 30 miles on foot to gather a two day supply of cooking fuel wood. In other parts of the world increasingly high rates of malnutrition are caused by a lack of fuel. Basic grain foods cannot be cooked without cooking fuel and water infected with chronic bacteria must be heated (boiled) before drinking. Continued gathering of wood cooking fuel by chopping down trees has resulted in eroded hill sides with loss of precious topsoil thus reducing their ability to grow food (Regli, 2003).

Today fresh water demand is increasing continuously, because of the industrial development, intensified agriculture, improvement of standard of life and increase of the world population. Only about 3 % of the world water is potable and this amount is not evenly distributed on the earth. On deserts and islands where underground water is not readily obtainable and the cost of shipping the places is high it is worthwhile to take into consideration of producing potable water from saline water, using solar energy that is in abundance in deserts (Regli, 2003).

Large quantities of fresh water are required in many parts of the world for agricultural, industrial and domestic uses. Lack of fresh water is a prime factor in inhibiting regional economic development. The oceans constitute an inexhaustible source of water but are unfit for human consumption due to their salt content, in the range of 3 % to 5 %. Seawater and sometimes brackish water desalination constitute an important option for satisfying current and future demands for fresh water in arid regions. Desalination is now successfully practiced in numerous countries in the Middle East, North Africa, southern and western US, and southern Europe to meet industrial and domestic water requirements (Muafag, 2007).

The supply of drinking water is a growing problem in most parts of the world. More than 80 countries which between them have 40 % of the world's population, suffer from this problem. To have this problem solved, new drinking water sources should be discovered and new water desalination techniques be developed. In many countries, fossil fuel burning water desalination systems are currently used. These systems can be up to 10 ton/day in capacity. The main water desalination or purification methods are distillation, reverse osmosis and electro dialysis. For bigger systems, reverse osmosis and electro dialysis are more economical, but for smaller ones, simple solar stills could be preferred because of their low costs. These days, in a number of countries including West-Indian Islands, Kuwait, Saudi Arabia, Mexico and Australia, these types of distillation units exist (Muafag, 2007).

Desalination has become increasingly important in providing an economically viable solution to the problem of decreasing fresh water resources. There are many factors to take into consideration to make a new technology sustainable. As we begin the 21st century, we must look towards cleaner sources of energy. Fossil fuel resources will soon be expired due to our rate of consumption. Cleaner energies such as natural gas, solar power, and photovoltaic technology must be integrated into desalination technology.

In recent years, desalination of water has been one of the most important technological works undertaken in many countries. Many areas in Middle East have little or no natural water supplies which can be used for human consumption and, hence, depend heavily on water produced by desalination. Several methods of solar water desalination are known. The utilization of solar energy for water desalination is becoming more attractive as the cost of energy continuously increases. Solar desalination is particularly important for locations where solar intensity is high and there is a scarcity of fresh water (Badran, 2007). The methods of solar water desalination are classified according to the way in which solar energy is used; the best-known method is the direct use of solar energy.

Small production systems such as solar stills can be used if fresh water demand is low and the land is available at low cost. High fresh water demands make industrial capacity systems necessary. These systems consist of a conventional seawater distillation plant coupled to a thermal solar system. This technology is known as indirect solar desalination. Many small size systems of direct solar desalination and several pilot plants of indirect solar desalination have been designed and implemented. Nevertheless, in 1996 solar desalination was only 0.02% of desalted water production (El-Sabaii, 2009).

Another advantage of desalination is that it will never run out its raw material. Because the facility is located right next to the ocean, and the ocean is so vast. Because of this, desalination is a drought-proof resource that is constantly able to produce fresh water regardless of the amount of rainfall (Badran, 2007). This is a great advantage if the desalination process is located in an agricultural area.

For people concerned about the quality of their municipally-supplied drinking water and unhappy with other methods of additional purification available to them, solar distillation of tap water or brackish groundwater can be a pleasant, energy-efficient option. Construction and operation of a single basin solar still is very simple. A black-painted basin contains brackish or sea water, which is enclosed in a completely air tight area formed by a transparent cover. Incident solar radiation passes through the transparent cover. The black basin absorbs the radiation. Consequently, water contained in the basin is heated and evaporates in the saturated conditions inside the still. Water vapour rises until it comes in contact with the cooler inner surface of the cover. There it condenses as pure water, runs down along the cover bottom surface due to gravity and is collected using a container (Badran, 2007).

For many people, clean and safe drinking water can only be acquired at a premium price and by purchasing and hauling potable water from public authorities. On the other hand, water obtained from shallow wells, rivers, and lakes may however not meet the World Health Organization (W.H.O) drinking water standards. It might be laced with high arsenic, fluoride, pathogens, industrial effluent, etc. Solar distillation offers a real and effective solution to clean this water supply on-site (Chewe, 2013).

Efforts to develop solar distillation technology and apply it to meet W.H.O drinking water standards have been on going. Various solar thermal technologies and designs have been studied and analysed in the context of optimizing the performance of solar heating in solar stills. The design parameters for these solar collectors with improved technologies have been discussed along with analysis of the impact of integration of various technologies applied to enhance their performance. Modelling and simulation investigations carried out for predicting the performance of the solar still and its function is also presented in this report (Chewe, 2013).

Most rural areas in Zambia face serious water supply issues that are comparable to those found in many parts of the developing world. One leading solar energy technology in particular that can literally revolutionize water quality throughout the less developed world with widespread adoption is solar distillation. This technology not only purifies water sources, but also effectively desalinates. Purifying water through distillation is a simple yet effective means of providing drinking water in a reliable and cost-effective manner. Solar stills effectively eliminate all water borne pathogens, salts, and heavy metals (Chewe, 2013). Solar distillation produces ultrapure water that is superior to most commercial bottled water sources.

Solar water distillation is not a new process, but it has not received the attention that it deserves. Nearly anyone is capable of building a still and providing themselves with completely pure water from very questionable sources.

One practical way of improving the production rate of distilled water is by using reflectors. They reflect rays that do not fall directly onto the water to be distilled. Solar reflectors have successfully increased solar radiation in food drying and cooking, water heating, building heating, and in various agricultural applications by concentrating solar radiation (Nichols, 1993). The use of reflectors enhances distilled water output without substantially increasing the cost of the still.

1.2 PROBLEM STATEMENT

The lack of safe and clean drinking water sources is one of the problems faced in most rural communities in Zambia. Water in these communities is mostly obtained from shallow wells and rivers. However, this water might be potentially contaminated with harmful substances such as coliforms and therefore unsafe for drinking. With the rising costs of both water transportation and distillation processes such as multistage flash, vapour compression, reverse osmosis, electrolysis, phase change, and solvent extraction, solar distillation is a simple and clean technology which can be used to distil brackish or polluted water into drinkable water.

Being able to predict solar still performance from long-term solar irradiance, air temperature, and cloud cover data, while taking into account meteorological variations, will prove to be a novel scientific investment to better the quality of life for Zambians and many people in need of potable water. Solar water stills can be used to eliminate harmful substances from contaminated water by treating it using free solar energy before it can be consumed.

1.3 RATIONALE

Performance improvement of solar water distillation systems has been slow. Perhaps this is because it is such a low-tech and flexible solution to water problems. One way of improving still performance to meet ever growing population needs for clean and safe drinking water especially in rural areas is by using reflectors. Reflectors are cheap and can be used to improve still performance by reflecting a good amount of solar radiation towards the potentially contaminated water. The improved system should still be relatively cheap, portable, and depends only on renewable solar energy.

1.4 OBJECTIVES

1.4.1 Main objective

- To investigate the quantity of distillate produced from solar water stills with and without reflectors.

1.4.2 Specific objectives

- To develop a small scale solar water still prototype.
- To test and check whether the distilled water produced adheres to World Health Organization (W.H.O) standards.

CHAPTER 2

2 REVIEW OF LITERATURE

2.1 HISTORICAL BACKGROUND

Solar distillation of water is without doubt, one of the few possibilities to satisfy the water needs in many regions of the world in a sustainable way. It is an ancient process that human beings have learnt in order to satisfy different needs. Aristotle clearly explained in his writings the evaporation process as part of the water cycle in nature and the ancient Egyptians showed solar distillation in their paintings and hieroglyphics. However, the earliest documented work on solar distillation was by Arab alchemists in the 16th century (Baum, 1970).

Full accounts of solar stills within the context of seawater desalination have been presented where an extensive description of various designs of solar stills, from the single-box still to the sophisticated multiple-effect distiller and greenhouse-inclusive types are described. The first conventional solar still plant was built in 1872 by Charles Wilson in the mining community of Las Salinas in Northern Chile. This still was a large basin-type still used to supply fresh water from brackish feed water to the community, with a total capacity of about 23 m^3 per day and lasted 40 years until the mines were exhausted (Cooper, 1973).

Solar distillation is one of the oldest methods used to produce fresh water for different basic human needs. Manufacturing and operation advances of conventional basin and portable solar stills were extensive during World War two (WWII). A purely theoretical, finite-difference model for the energy balance of the glass cover and the brine was presented by Cooper in 1969. The influence of several parameters, such as initial mass of brine, with and without thermal insulation under the basin was analysed (Cooper, 1973). Several useful modifications have since been established using lumped-parameter equations for the energy balance.

Solar distillation is one of the most important and complete works in the solar distillation field. It describes the heat transfer model of a solar still, the energy balances and the results of distillation yield as a function of time. Also, there is an extensive description of systems, configurations and applications of solar stills along with certain aspects of engineering economics (Moustafa, 1979).

2.2 SOLAR DISTILLATION

Solar distillation systems have been put into practice especially in countries where ample solar radiation is available, in order to overcome the ever increasing shortage of fresh water. The distillation of potentially contaminated water is accomplished by exposing thin layers of this water to solar radiation and condensing the resulting water vapour onto a transparent cover in such a way that it can be collected in a trough. A device capable of performing this process is known as a solar still (Cooper, 1973).

2.2.1 Definition

A solar still is a device that produces potable water from dirty water using energy from the sun. It has relatively low productivity but competitive to the other purifying methods due to its relatively low cost, simplicity in design and operation as well as maintenance. The addition of reflectors onto the still enhances production rate of distilled water and using them as solar concentrators may be one of the cheapest available means to improve overall still performance (National Renewable Energy, 2008).

2.2.2 Basic components

Basin still consists of the following basic components:

- A basin.
- Support structures and trough.
- Glazing.
- A distillate (Malik, 1982).

In addition to these, ancillary components may include:

- Insulation (usually under the basin).
- Sealants.
- Piping and valves.
- Facilities for storage.
- A reflector to concentrate sunlight (Malik, 1982).

2.2.3 Details of main parts of the system

2.2.3.1 Still basin

It is the part of the system in which the water to be distilled is kept. It is therefore essential that it must absorb solar energy and necessary that the material must have high absorptivity and less reflectivity. This is the criterion for selecting the basin materials. Blackened galvanised iron will be used (Malik, 1982).

2.2.3.2 Side walls

Generally provide rigidness to the still. But technically it provides thermal resistance to the heat transfer that takes place from the system to the surrounding. So it must be made from material that possess a low value of thermal conductivity and should be rigid enough to sustain its own weight and the weight of the top cover (Malik, 1982).

2.2.3.3 Top cover

The passage from where irradiation occurs on the surface of the basin is the top cover. Also it is the surface where condensate collects. The properties of the top cover are:

1) Transparent to solar radiation.

2) Non-absorbent to water.

3) Clean and smooth surface (Malik, 1982).

2.2.3.4 Channel

The condensate that is formed slides over the inclined cover and falls in a passage. This passage which fetches out the pure water is called channel.

2.2.3.5 Supports for top cover

The frame provided for supporting the top cover is optional, i.e. it can be used if required. The only change is the need to make the model as vacuumed as possible. So it will have to be airtight by sticking tape on the corners of the glass and at the edges of the box from where the possibility of the leakage of inside hot air is (Malik, 1982).

2.2.3.6 Reflectors

The reflector material should have a high reflectance and low absorptivity. It will be mounted on top of the still at fixed angles. A pair of reflectors will be used and will be made of aluminium foil (Nichols, 1993).

2.3 NEEDS SERVED BY SOLAR DISTILLATION

Solar distillation could benefit developing countries in several ways:

- Solar distillation can be a cost-effective means of providing clean water for drinking, cooking, washing, and bathing which are the four basic human needs.
- It can improve health standards by removing impurities from questionable water supplies.
- It can help extend the usage of existing fresh water in locations where the quality or quantity of supply is deteriorating.
- Solar distillation generally uses less energy to purify water than other methods.
- Solar distillation will permit settlement in sparsely populated locations, thus relieving population pressures in urban areas (Medugu, 2006).

2.3.1 Justification of solar still use

A solar still will operate with extremely low operation and maintenance costs. Over a long period, it is valid to assume that 85 per cent of the cost of water from the still will be chargeable to the costs of buying it; the remainder to operation and maintenance. It is easy to calculate the return of investment on that still. Say you have one that produces a daily amount that would cost $1 to buy in water bottles; then will return you $365 per year. If the still had cost you $365, then it paid for itself in one year; if five times that much, then five years, etc. not counting interest. The cost of feeding water into the still is pretty small, but will increase the pay-out period. Studies show that the pay-out period tends to fall between two and five years, depending on the still size and features (Sobsey, 2002).

2.3.2 Water quality

Effective microbiological purification of water is an important consideration in the prevention of water-borne diseases and their transmission. However research on technology advances is still required and this study is also aimed at assessing the effectiveness of solar pasteurization as a water disinfectant method suitable for the production of potable water in rural areas (World Health Organisation, 2002).

In general, the following determine water contamination:

1) Suspended solids.
2) Biodegradable organic compounds.
3) Pathogenic organisms.
4) Toxic compounds (World Health Organisation, 2002).

Municipal water does not contain toxic compounds. Since the number of compounds present is almost limitless, consideration is normally restricted to a few general classes of compounds (World Health Organisation, 2002). The quality of water can be defined in two ways:

1) Physical, chemical and biological characteristics.
2) Suitability of water for a specific use.

The primary aim of guidelines for drinking water quality is the protection of public health.

2.3.3 Health-related drinking water contaminants

2.3.3.1 Biological

Infectious diseases caused by pathogenic bacteria, viruses and protozoan by parasites are the most common and widespread health risk associated with drinking water. These biological constituents of water, related primarily to the resident aquatic population of microorganisms just mentioned, directly impact water quality. The most important impact is the transmission of diseases by pathogenic organisms in water (American Water Works Association, 1998).

2.3.3.2 Chemical

The health risk due to toxic chemicals in drinking water differs from that caused by microbial contaminants. There are a few chemical constituents of water that can lead to acute health problems mainly through massive accidental contamination of a supply. Moreover, experience has shown that in such incidents, the water usually becomes undrinkable owing to unacceptable taste, odour and appearance. The fact that chemical contaminants are not normally associated with acute effects places them in a lower priority category than microbial contaminants, the effects of which are usually acute and widespread. Indeed it can be argued that chemical standards for drinking water are secondary consideration in a supply subject to severe bacterial contamination (American Water Works Association, 1998).

2.3.3.3 Physical

The acceptability of drinking water to consumers can be influenced mainly by many constituents e.g. those which also affect the taste or odour of water may have no direct consequence or relevance to health at the concentration at which they normally occur in water but nevertheless may be objectionable to consumers for various reasons. The concentration at which such constituents are offensive to consumers is dependent on individual and local factors, including the quality of the water to which the community is accustomed and a variety of social, economic and cultural considerations. These are the physical parameters such as colour, odour, taste, turbidity, hardness, etc. (American Water Works Association, 1998).

2.4 OPERATING PRINCIPLES

It takes a lot of energy for water to vaporize. While a certain amount of energy is needed to raise the temperature of a kilogram of water from 0˚ to 100˚ C, it takes five times that much to change it from water at 100˚ C to water vapour at 100˚ C. Practically all this energy, however, is given back when the water vapour condenses. The salts and minerals do not evaporate along with the water. Ordinary table salt does not turn into vapour until it gets over 1400˚ C, so it remains in the brine when the water evaporates (Sanyaolu, 2002).

It is not necessary for the water to actually boil to bring about distillation. In a solar still, it will usually turn out even more pure, because during boiling the breaking bubbles may contaminate the product water with tiny droplets of liquid water swept along with the vapour. The solar distillation process is shown in Figure 1. Solar radiation passes through a glass, heats up the potentially contaminated water causing the water to vaporize. The vapour rises and condenses on the underside of the cover and runs down into distillate troughs (Sanyaolu, 2002).

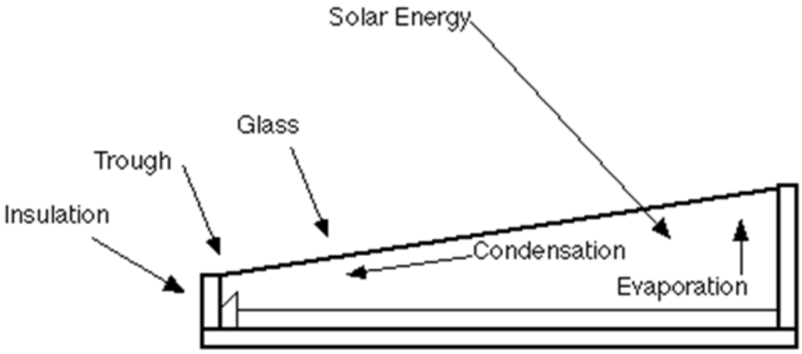

Fig 1. Solar distillation process

Source: (Sanyaolu, 2002)

In most units, less than half the calories of radiance falling on the still are used for heating. This energy is however necessary to produce the distilled water. Commercial stills sold to date have had an efficiency range of 30 to 45 per cent with maximum efficiency just over 60 per cent. Efficiency is calculated in the following manner:

$$\text{Efficiency} = \frac{\text{Energy required for the vaporization of the distillate that is recovered}}{\text{Energy in the sun's radiation that falls on the still}} \quad \ldots\ldots\ldots [i]$$

Provided the cost does not rise significantly, efficiency increase of a few per cent is worth working out. Improvements are principally to be sought in materials and methods of construction (Malik, 1982).

2.5 COMPARATIVE ADVANTAGE

2.5.1 Concentrating collector still

A concentrating collector still, as shown in Figure 2, uses flat reflectors to focus sunlight onto an enclosed evaporation vessel. This concentrated sunlight significantly raises the temperature which is used to evaporate the contaminated water. This type of still is capable of producing from 3.9 to 6.5 litres per day per square meter of condensing surface area. This type of output far surpasses other types of stills on a per square meter basis (Nichols, 1993).

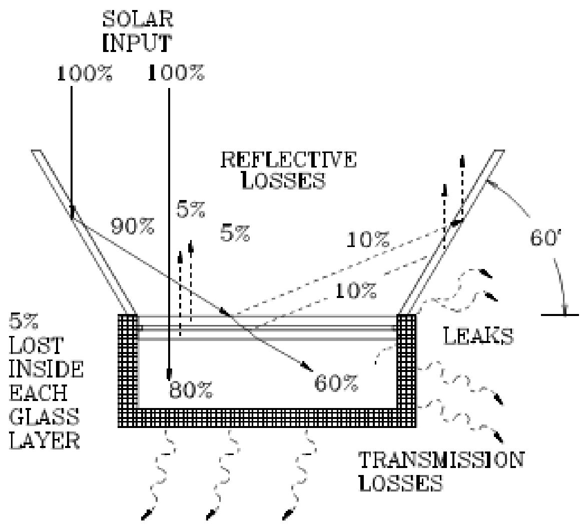

Fig 2. Solar still with reflectors

Source: (Nichols, 1993)

Many approaches have been tried to raise the distillate production rate. The "inclined-tray" still is one of them and is accomplished by using many small pans in a stair step arrangement. With this arrangement, total sunlight striking the aperture of the glass remains more constant, and the light which glances off the bottom of water of the small tray warms the one above it thereby improving performance (Ronnelid, 2000).

While this is a substantial advantage, it is the only advantage of this design, and it must be weighed against the disadvantages of higher associated costs with putting many small pans versus only one enclosure, and, in the most probably, higher installation costs due to holding the end of the pan higher off the supporting surface, and protecting it against wind loads.

Using an inclined-tray still is only one solution to the problem due to annual variation in higher latitudes. Buying an extra-large still will produce enough distilled water but may prove to be more costly than adding reflectors (Ronnelid, 2000).

There is likelihood that there will be more water than needed in summer by;

- Using less water in winter and/or using some tap water.
- Buying supplemental water in winter.
- Storing some of the excess distilled water made in summer or fall for use in winter.
- Installing a mirror behind the basin to reflect additional sunlight back into the still in winter.

Much work has been done to try to obtain lower condensing temperatures, temperature thereby increasing the difference between the heated feed water and the condensing surface. This approach undoubtedly derives from 100 years of steam power engineering, in which it is most important to get the steam temperature high and the condensing temperature low to gain efficiency. But this principle does not hold for a solar still. True contents of steam for power generation are pure steam, whereas in a solar still both air and water vapour (Ronnelid, 2000).

The practical effect of this is that a still operating in a hot climate will produce typically as much as one-third more water than the same unit in a cooler climate. By the same token, cooling the glazing cover of a solar still by spraying water on it or blowing air over still produce more it does not help the distillate.

In summary, solar stills have:

- High initial costs.
- The potential to use local materials.
- The potential to use local labour for construction and maintenance.
- Low maintenance costs (ideally).
- No energy costs (not subject to fuel supply interruptions).
- Few environmental penalties.
- In residential sizes, no subsequent costs for delivering water to the end user (Hikmet, 2005).

Most competing technologies are:

- Low in initial costs.
- Dependent on economy of scale.
- High in operating and maintenance costs.
- High in energy input costs.
- Low in local job creation potential.
- Vulnerable to changes in energy supply and costs (Hikmet, 2005).

Compared to hauling purified water in bottles or tanks, solar distilled water would almost always be much less expensive. The cost of boiling water to sterilize it should be competitive to using a still in many situations. Although the materials used in building a still will probably always be expensive, mass production could ultimately drive down the unit cost per still (Chargoy, 1990).

Unlike other techniques of water purification, solar stills are more attractive. The initial capital cost of stills is roughly proportional to capacity, whereas other methods have significant economies of scale. For the individual household, therefore, the solar still is most economic.

Two identical stills are to be built, one with and another without reflectors. Of the two, the one with reflectors will be expected to produce significantly more distilled water. Its distillate is not expected to be of better quality.

2.6 MARKET POTENTIAL

Three potential markets exist for solar stills. First, a solar still can be economically attractive in almost any place in the world and where a source of water is available to feed the still. Second, many people who boil their water to kill germs could use a solar still for the same purpose. It will take more work to demonstrate this function adequately, but early tests have made it seem highly promising. A third market is in arid regions, whose untapped water resources may be sufficient to economically provide a population with potable water (Chewe, 2013).

2.7 CHOOSING THE TECHNOLOGY RIGHT FOR YOU

2.7.1 Factors to consider

Solar energy is an excellent choice for distillation of water in Third World countries that meet the following conditions:

- Expensive fresh water source $1 or more per 1000 gallons.
- Adequate solar energy.
- Available low-quality water for distillation (Baum, 1970).

Other conditions suitability for solar stills are:

- Competing technologies that require expensive conventional wood or petroleum fuels.
- Isolated communities that may not have access to clean water supplies.
- Limited technical manpower for operation and maintenance of equipment.
- Areas lacking a water distribution system.
- The availability of low-cost construction workers (Baum, 1970).

The greater the number of these conditions present, solar stills are likely to be the more viable alternative. If the cost of the water produced by a still over its useful life is less than alternate methods, it is economical to pursue. Finally, the acceptance of solar distillation will depend greatly on how well one understands and handles the many social issues and cultural constraints (Mfune, 2008).

Stills built for village use require community cooperation that may be foreign to some cultural groups. Family-sized solar still units are therefore encouraged to improve care and maintenance of the still which a household has control over (Mfune, 2008).

Potential users who think they will find distilled water tasteless or not in keeping with what they are accustomed to may become disappointed and possibly abandon altogether the thought of drinking the water. The problem of taste must be dealt with early on so as not to give people a reason to respond negatively to the technology as a whole.

In some societies, conflicts may arise over whether it is the responsibility of the man or the woman on the household to operate the solar still. Not dealing with this issue early on could result in the household's total rejection of the technology. If solar distillation is perceived to be a threat to a community's traditional lifestyle, the community may reject the technology. Such concerns can be headed off if the technology is designed appropriately from the start and introduced at the proper time (Mfune, 2008).

Moreover, a community is more likely to accept the technology if it recognizes the importance of clean water and considers it a priority to the degree that it is willing to change certain aspects of its lifestyle.

2.8 OPERATION AND MAINTENANCE OF SOLAR STILL

2.8.1 Operating requirements of the still

2.8.1.1 Protecting distilled water from contamination

Protecting a solar still against the entry of insects and polluted rainwater is important. After installations, one must:

1) Disinfect the interior of the still and tubing with chlorine compounds (adding a few spoonful's of laundry bleach to a few litres of water does the job effectively).
2) Provide a vent in the feed tube at the still, screened with fine galvanised iron screen filter washer in a pipe fitting, turned downward to prevent entry contaminated of rainwater (International Energy Agency, 2011).

If these precautions are not taken, flying insects, attracted by the moisture, might find their way in and die in the distillate trough. Preventing contamination in a storage reservoir is a little more difficult, as the daily high temperature is not available to pasteurize the water. Nevertheless, with diligent attention to detail, the system can be used for decades without contamination (International Energy Agency, 2011).

2.8.1.2 Filling and cleaning a basin still

Filling a basin still is a batch process done once a day at night or in the morning. This has however proved to be cumbersome and hence the introduction of a flow control valve that supplies water constantly to the still from an external source. With a still of this design, about 5 to7 per cent of the day's total distilled water is produced.

Stills refilled between three hours or more after sundown and up to one or two hours after sunrise will cause little, if any, loss of production. This has been the case in traditional stills. A vent allows air to enter and exit the still daily during the operation and refilling but the incorporation of a flow control valve from the water supply tank makes the operation of the still function even without vents. This is also part of the improvement as the still will not drain completely (International Energy Agency, 2011).

Cleaning the still two times a week would keep it a little cleaner than once even though continuous flow of water helps prevent stagnation during none operation hours like night time. Therefore draining the still during these hours could be worth doing, provided the cost of feed water is nominal. In our case, the feed water is abundant therefore the cost is not a problem. A rapid flushing can be applied but not required; a gentle trickle does the job (International Energy Agency, 2011).

2.9 FACTORS INFLUENCING SOLAR STILL OPERATING PERFORMANCE

In this section, some important factors that influence the rate of production of distilled water are discussed. These include:

1) Climatic factors.
2) Thermal loss factors.
3) Solar still design factors (El-Sabaii, 2009).

2.9.1 Climate factors

2.9.1.1 Radiation

The amount of solar radiation a solar still receives is the single most important factor affecting its performance. The greater the amount of energy received, the greater will be the quantity of distilled water produced. It is for this reason that solar stills are expected to produce less distilled water in winter than summer, which is a problem. To some extent, the demand for drinking water also varies with the seasons; the ratio may be 2 to 1, by as much in summer over winter (Kyocera, 2009). But the variation of annual sunlight affecting a still's solar distillation rate is greater in regions well outside the tropics.

In tropics at latitudes of less than 20˚, variation in the annual sunlight is probably well under 2 to 1, so it may not be a problem in these regions. Zambia at latitude 15.4˚ falls under this category. The further away from the equator, the greater the annual sunlight variation (Kyocera, 2009). Note that there are other methods available for large distillation plants. However, because they fall outside scope of this project, they are not discussed here.

2.9.2 Thermal loss factors

Production is also associated with the thermal efficiency of the still itself. This efficiency may range from 30 to 60 per cent depending on still construction, ambient temperatures, air velocity, wind, and solar energy availability. Thermal losses for a typical still vary by season. Details of these losses will be further discussed in chapter 3.

2.9.3 Solar still design factors

Slope of the transparent cover and the angle at which the reflectors are set influences the amount of solar radiation entering a solar still. When sunlight strikes glass straight on, i.e. at 90˚ to the surface, about 90 per cent of the light passes through. This is the reason why the slope angle will be set to latitude angle and will face true north (Kyocera, 2009).

The still with reflectors will shadow part of the glass cover early in the morning (before nine o'clock) and late in the afternoon (after fifteen o'clock). This is because the optimum reflector angle of about 30˚ from the vertical denotes 2 hours of the suns travel from the vertical (i.e. 1 hour = 15˚) (Nichols, 1993). Studies show that any angle between 27˚ and 35˚ will produce good results. This is shown in figure 3.

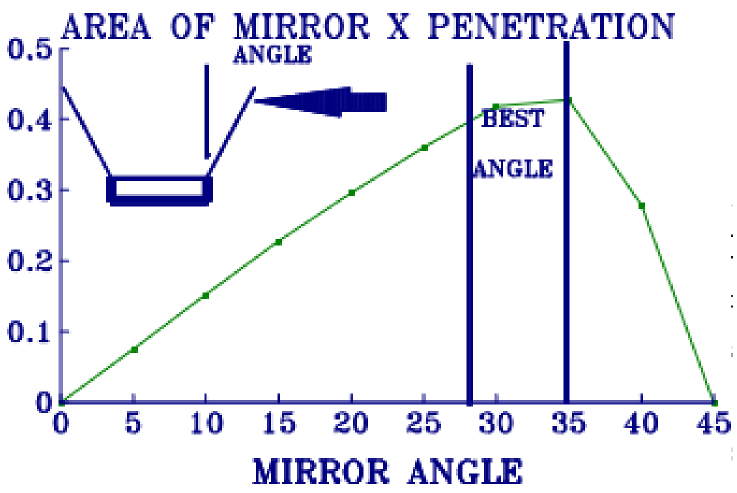

Fig 3: Optimum reflector angle

Source: (Nichols, 1993)

The percentage of light that enters the glass from the reflectors is maximised between 0˚ and 60˚. This range is however reduced to between 27˚ and 35˚ because the rest of the values outside this range do not give the desired penetration percentages. This is shown in figure 4.

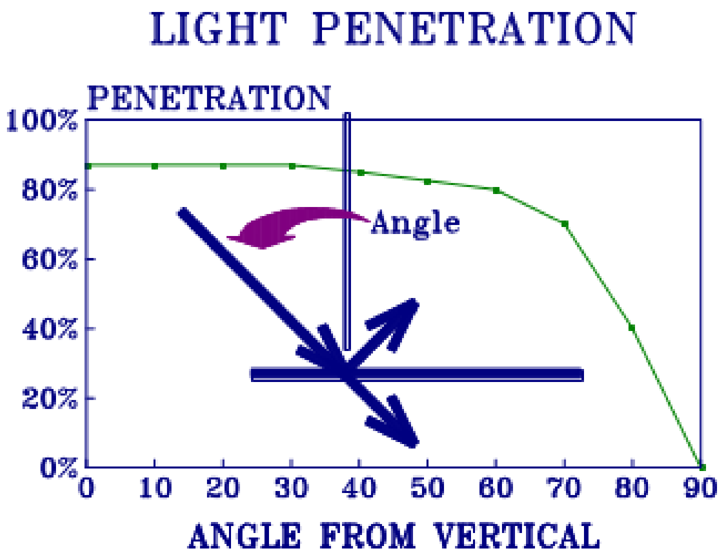

Fig 4: Penetration percentage with varying angles

Source: (Nichols, 1993)

The slope of the glass cover does not affect the rate at which the distillate runs down its inner surface to trough for collection. A common misconception was that the glass cover must be tilted to get the water to run off. This may have arisen from the fact that ordinary window glass, as it comes from factory, has an oily film on it. But if the glass is clean, the water itself will form film wise condensation on it and will be able to run off at a slope as little as 10˚ (Kyocera, 2009).

There are three reasons why it is best to use as low a slope as possible:

1) The higher the slope, the more materials are needed for cover and the more glass and support a given area of the basin will be required.
2) The higher slope also increases the overall volume and weight of the still. Hence costs will also rise.
3) Setting the glass at a high slope increases the volume of air inside the still and this lowers the efficiency of the system. A glass cover that is not more than 5 and 7 cm from the water surface will operate more efficiently. Conversely, as glass-to-water distance increases, heat loss due to convection becomes greater, causing the still's efficiency to drop. It also increases the condensing surface relative to the absorber, which reduces operating temperatures in the still, and is clearly disadvantageous (Kyocera, 2009). Hence a high slope of cover glass is to be avoided.

It is clear that a solar still should be built in a way that will get the water as hot as possible, and keep the water as close to the glass as possible. This is achieved by keeping the glass cover at a minimum distance from the water. Practical terms fall between 5 and 7 cm from water surface, and by minimizing the depth of water in the pan, to about 1.5 cm (Kyocera, 2009).

2.10 MAINTENANCE REQUIREMENTS OF BASIN STILLS

It is inevitable that some minerals are deposited at the bottom of the basin. In most situations, the amount deposited is so small that it creates no problem for decades. Nevertheless ways of handling the build-up of mineral deposits have to be considered. Excessive mineral deposits become the normal absorber. An accumulation of these deposits changes the interior surface of basin from its original black colour to one reflecting some sunlight, causing a 10 per cent drop in still production (World Health Organisation, 2002).

To offset this reduction, the still can simply be made 10 per cent larger than it would need to be if it were cleaned out periodically. Waters high in alkalis will deposit a whitish scale at the bottom and sides of the basin. In fact, almost any feed water will do so especially if the basin is allowed to dry out. In some cases, the alkaline water may form a crust of scale which is held on the water's surface by air discharged when the feed water bubbles that are heated.

In the vast majority of stills, dust accumulates on the cover glass but it does not keep building up; it is held more or constant by the action of rain and less dew. This "normal" accumulation causes production to drop from 5 to 15 per cent. This will be offset simply to make the still 10 per cent larger than would need to be if kept clean. However, in unusually dusty areas, if the still is large enough and that a caretaker is available at modest cost, cleaning the glazing is justified. 10 per cent of 10,000 litres per day may be enough to justify cleaning the cover once a month in the dry season (World Health Organisation, 2002).

2.10.1 Repair and replacement of basin still components

As with all devices, the components of a basin still may need to be repaired or replaced from time to time. The frequency depends on the type of material used to construct the still.

Premium materials will require almost no maintenance, but will entail a higher capital cost because many of the materials must be imported materials.

Use of cheaper materials subject to degradation will almost certainly lower the initial cost, but will increase the amount of maintenance. Even so, if the long-term cost of maintenance and the lower initial cost are less than the higher initial cost for premium materials, this may present a better option, especially if cost of capital is high. This is called "life cycle cost analysis," and it is strongly recommended (World Health Organisation, 2002).

2.10.2 Skills required in building, operating, and maintaining basin stills

Craftsmanship and attention to detail in construction are important for an efficient, cost-effective still. In addition, supervisory personnel must be on hand who know how to size stills to meet a community's water supply needs. These should know how to orient stills, know the techniques and familiarise with required construction, have the ability to train others in the construction, operation and maintenance of stills.

Finally, it is important to ask local workers to participate in the planning and construction phases of a solar still project to get the indigenous population to accept the technology. A sense of pride in the building of the project may well mean the difference between long-term success and failure of the project (Chewe, 2013).

CHAPTER 3

3 METHODOLOGY

3.1 DESIGN

3.1.1 Product design specifications

The materials used for this type of still should have the following characteristics:

- Materials should have a long life of about 5 years under exposed conditions or be inexpensive enough to be replaced upon degradation.
- Should be steady enough to resist wind damage and slight earth movements.
- Should be nontoxic and not emit vapours or instil an unpleasant taste to the water under elevated temperatures.
- Should be able to resist corrosion from potentially contaminated water and distilled water.
- Should be of a size and weight that can be conveniently packaged and carried by local transportation.
- Should be easy to handle in the field.

Although local materials should be used whenever possible to lower initial costs and to facilitate any necessary repairs, solar stills made with cheap materials will not last as long as those built with more costly, high-quality material. With this in mind, one must decide whether to build an inexpensive and thus short-lived still that needs to be replaced or repaired every few years, or build something more durable and lasting with the hope that the distilled water it produces will be cheaper in the long run (Chargoy, 1990).

Building a more durable still that will last at least 5 years seems to be worth the additional investment. Choosing materials for the components in contact with the water represents a serious problem. Many plastics will give off a substance which can be tasted or smelled in the product water (Chargoy, 1990).

As a general guide, a useful test can be performed by boiling a sample of the material in a cup of good water for half an hour then letting the water cool before smelling and tasting it. This is a considerably accelerated test of what happens in the still. If you cannot tell any difference between the test water and that you started with, the material is probably safe (Baum, 1970).

3.1.2 Special design variations

The majority of information presented thus far is centred on the basin-type solar still because it is the easiest to construct and may use a wide range of materials, on different locales, making it adaptable.

In addition to these options, there are other ways to design the still efficiency or to increase its potential to produce potable water. One of them is equipping the basin still with reflectors. Some stills equipped with reflective materials have the potential to increase the amount of sunlight falling on the still without having to increase the area of the still. Aluminium sheets are used for this reflective purpose.

3.1.3 Material selection factors for still basin

This section describes the basin component, the range of materials available for its construction, as well as its advantages and disadvantages.

The basin contains the potentially contaminated water that will undergo distillation. As such, it must be waterproof and dark (preferably black) so that it will absorb sunlight and convert it to heat. It should also have relatively smooth surface to make it easier to clean any sediments from it. It is important to state that no one construction material is appropriate for all circumstances or locations.

An infinite number of combinations of materials will serve these functions. The membrane that holds water, for example, should be stiff enough to support the water. The basin should also be rigid enough to support the glass. In short, a component need not satisfy two functions at the same time (Schoneveld, 2012).

Local materials should be selected to do each job separately, and then put them together. In selecting materials for a solar still, there are almost always trade-offs. Money can be saved on materials, but one may lose much in productivity or durability (Schoneveld, 2012).

3.1.3.1 Material selection for still construction

The objective is to lower the cost of water on a 5-year life cycle cost basis. To achieve this, the best materials for building a basin still should be used. These are:

- Black tank paint to darken the bottom of the basin.
- About 25 to 38 millimetres of insulation around the basin (this should be high-temperature polystyrene).
- Bottom covering of lightweight galvanized iron.
- Galvanised iron trough.
- Regular double-strength window glass.
- Extruded gaskets, compressed into final position.

3.1.3.2 Cost/Economics

The cost and economics of solar stills depend on many variables, including:

- Cost of water produced or obtained by competing technologies.
- Water requirements.
- Availability of sunlight.
- Cost of locally-available materials.
- Cost of local labour.
- Cost of imported materials.
- Loan availability and interest rates.

3.2 THEORETICAL ANALYSIS

A schematic diagram of the still is shown in figure 5 and shows some of the parameters relating to the theoretical equations given in this section.

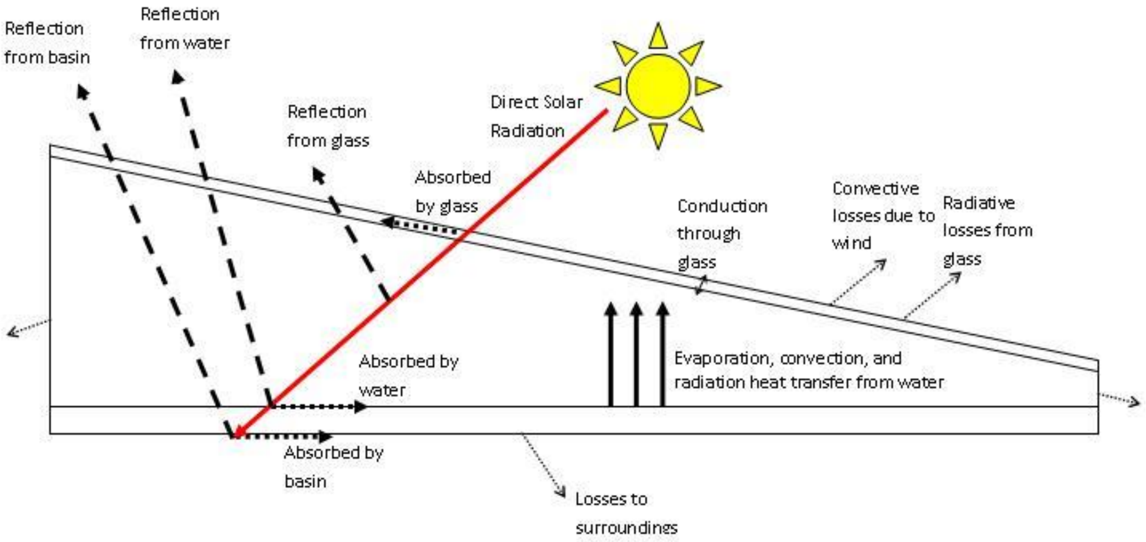

Fig 5. Schematic diagram of still showing equation descriptions

Source: (Tamini, 1987)

3.2.1 Solar flux absorption

Solar flux absorbed by the glass cover is

$$\alpha'_g = (1 - R_g)\ \alpha_g \tag{1}$$

Solar flux reflected by the water mass

$$R'_w = (1 - R_g)\ (1 - \alpha_g)\ R_w \tag{2}$$

Solar flux absorbed by the water mass

$$A'_w = \alpha'_w\ (1 - \alpha_g)\ (1 - R_g)\ (1 - R_w)\ \alpha_w \tag{3}$$

Solar flux absorbed by the basin

$$\alpha'_b = \alpha_b\ (1 - R_g)\ (1 - \alpha_g)\ (1 - R_w)\ (1 - \alpha_w) \tag{4}$$

Solar flux lost by the ambient, through water and glass cover, will be

$$L'_a = (1 - \alpha_b)\ (1 - R_g)\ (1 - \alpha_g)\ (1 - R_w)\ (1 - \alpha_w) \tag{5}$$

3.2.2 Energy balance

If the evaporation processes inside the still unit is considered as isobaric atmospheric process at thermal equilibrium, then all the absorbed solar radiation is utilized for evaporation and thermal losses. An energy balance for steady state around the water basin can be written as (Tamini, 1987):

Rate of energy in = Rate of energy out, that is,

$$(\alpha'_w - \alpha'_b)\ I(t)\ A_s = Q_{ew} + Q_{losses} \tag{6}$$

But

$Q_{ew} = m_w L$

$Q_{losses} = U'_L\ (T_w - T_a)\ A_s$ and $(\alpha'_w - \alpha'_b) = (\alpha\tau)_w$

Where:

Q_{ew} is the heat which is utilized by solar still for obtaining m kg of distilled water per m^2 per day;

U'_L is the overall heat transfer coefficient from water to ambient through top, bottom and sides of the still unit;

A_s is the area of the still;

T_w and T_a are the temperature of the water inside the still and ambient temperature respectively;

L is the latent heat of vaporization;

m_w is the daily output of the distillate.

Equation (6) can now be written as

$$Q_{ew} = m_w L = (\alpha\tau)_w\ I(t)\ A_s - U'_L(T_w - T_a)\ A_s \tag{7}$$

3.2.3 Heat transfer

The heat transfer in solar still is mainly classified into two ways, internal and external heat transfer. The details of various heat transfers in solar still are shown in Figure 6.

3.2.3.1 External heat transfer

The external heat transfer in solar still is mainly governed by conduction, convection and radiation processes, which are independent each other. The heat is lost from outer surface of the glass to atmosphere through convection and radiation modes. The glass and atmospheric temperatures are directly related to the performance of the solar still. So, top loss is to be considered for the performance analysis.

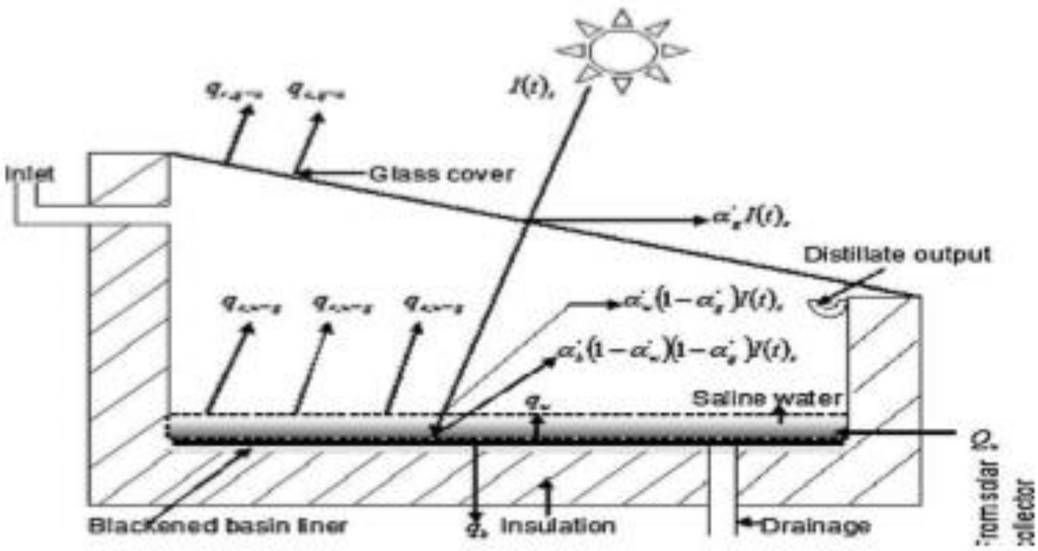

Fig 6: Energy flow of solar still

Source: (Hikmet, 2005)

The external heat transfer, radiation and convection losses from the glass cover to the outside atmosphere q_g can be expressed as

$$q_g = q_{rg} + q_{cg} \tag{8}$$

Where;

$$q_{rg} = \varepsilon_g \sigma \,(T_g^4 - T_s^4) \tag{9}$$

$$q_{cg} = h_{cg}\,(T_g + T_a) \tag{10}$$

T_g is the temperature of the glass and may be assumed to be uniform due to the small thickness of the glass cover;

T_a is the sky temperature;

ε_g is the emissivity of glass cover;

σ is the Stefan – Boltzmann constant;

h_{cg} is forced convective heat transfer coefficient from the glass to ambient air.

Equation (9) can also be written as

$$q_{rg} = h_{rg}\,(T_g + T_a) \tag{11}$$

With

$$q_{rg} = \varepsilon_g \sigma \left(\frac{T_g^4 - T_s^4}{T_g + T_a}\right) \quad (12)$$

By substituting equations (11) and (10) into equation (8) gives

$$q_g = h_{rg} + h_{cg}\,(T_g + T_a) = h_{1g}\,(T_g + T_a) \quad (13)$$

For the effect of free convection and radiation from the glass cover, h_{1g} is given as (Watmuff, 1977):

$$h_{1g} = 5.7 + 3.8v \quad (14)$$

Where;

v is the wind speed in m/s.

In case the radiation and convective losses are to be evaluated separately, the radiative heat transfer coefficient, h_{rg} can be obtain from equation (12) and the convective heat transfer coefficient, h_{cg} can be obtained from the relation (Watmuff, 1977):

$$h_{cg} = 2.8 + 3.0v \quad (15)$$

Heat is also lost from the water in the basin to the ambient through the insulation and subsequently by convection and radiation from the bottom or side surface of the still.

The bottom loss coefficient, U_b can be written as

$$U_b = \left(\frac{1}{h_w} + \frac{1}{h_b}\right)^{-1} = \left(\frac{1}{h_w} + \frac{1}{k_i/L_i} + \frac{1}{h_{cb}+h_{rb}}\right)^{-1} \quad (16)$$

Where; k_i and L_i are the thermal conductivity of air and the insulation thickness respectively.

The side heat loss coefficient, U_s can be approximated as

$$U_s = U_b \frac{A_{ss}}{A_s} \quad (17)$$

Where;

A_{ss} is the surface area in contact with water and A_s is the area of the basin of the still. U_s can be neglected if $A_{ss} << A_s$.

The rate of heat loss per m^2 from the basin liner to ambient can be written as;

$$q_b = h_b\ (T_b - T_a) \tag{18}$$

Where;

$$h_b = \left(\frac{L_i}{K_i} + \frac{1}{h_{cb}+h_{rb}}\right)^{-1} \tag{19}$$

3.2.3.2 Internal heat transfer

In solar still basically internal heat is transferred by evaporation, convection and radiation. The convective and evaporative heat transfers takes place simultaneously and are independent of radiative heat transfer.

The internal heat transfer mode, that is, the heat exchange from the water surface to the glass cover inside the still unit is governed by radiation, convection and evaporation. In this case, the water surface and the glass cover are considered as infinite parallel planes. The rate of radiative heat transfer, q_{rw} from the water surface to the glass cover for these infinite parallel planes is given by

$$q_{rw} = \varepsilon_g \sigma\ (T_w^4 - T_g^4) \tag{20}$$

$$q_{rw} = h_{rw}\ (T_w + T_g) \tag{21}$$

Where;

h_{rw} is the radiative heat transfer coefficient from the water surface to the glass cover and is given by (Watmuff, 1977):

$$h_{rw} = \varepsilon_g \sigma\ [(T_w^2 + T_g^2)(T_w + T_g + 546)] \tag{22}$$

Here T_w and T_g are measured in Kelvin.

Heat transfer occurs across humid area in the distillation unit by free convection, which is caused by the effect of buoyancy, due to density variation in the humid fluid, which occurs due to the temperature gradient in the fluid. Hence, the rate of heat transfer from the water surface to the glass cover, q_{cw} by convection is the upward direction through the humid fluid and can be estimated by

$$q_{cw} = h_{cw}\ (T_w - T_g) \tag{23}$$

The convective loss coefficient from the water surface to the glass h_{cw} is given as (Dunkle, 1961):

$$h_{cw} = 0.884\left[(T_w - T_g) + \frac{(P_w - P_g)T_w}{268.9x10^3 - P_w}\right]^{1/3} \tag{24}$$

Where;

P_w and P_g are the saturation partial pressures of water at water temperature and glass temperature, respectively. The mass transfer coefficient, h_e, in terms of convective heat transfer coefficient h_{cw} (equation (24)) is given by (Baum, 1970):

$$\frac{h_e}{h_{cw}} = \frac{L}{C_{pa}} \frac{M_W}{M_a} \frac{1}{P_T} \tag{25}$$

Where:

P_T is the total gas pressure;

M_w is the mass of water vapor;

M_a is mass of air and;

C_{pa} is the specific heat per unit volume at constant pressure of the mixture.

The rate of heat transfer per unit area from the water surface to the glass cover can be obtained by substituting the appropriate values for the parameters in equation (25) (Malik, 1982). Thus;

$$q_{ew} = 0.013 h_{cw} \, (P_w - P_g) \tag{26}$$

Cooper (1973) derived similar equation and is given as

$$q_{ew} = 0.0162 h_{cw} \, (P_w - P_g) \tag{27}$$

Rearranging equation (27) gives

$$q_{ew} = h_{ew} \, (T_w - T_g) \tag{28}$$

Where;

$$h_{ew} = 16.273x10^{-3} \; h_{cw} \, \frac{P_w - P_g}{T_w - T_g} \qquad \text{(Cooper, 1973)} \tag{29}$$

The values of P_w and P_g (for the range of temperature 10˚C - 90˚C) can be obtained from the expression (Chargoy, 1990):

$$P(T) = exp\left(25.317 - \frac{5144}{T+273}\right) \tag{30}$$

Where;

$P(T)$ is the saturated vapour pressure.

The hourly yield of the solar still is given as:

$$m_{ew} = h_{ew} \frac{(T_w - T_g)}{L} x3600 \qquad \text{(Tiwari, 1989)} \qquad (31)$$

3.2.4 Solar still efficiency

The thermal efficiency of solar still can be defined as the ratio of the amount of thermal energy utilized to get a certain amount of distilled water to the incident solar energy within a given time interval.

Further, the instantaneous efficiency of the still unit η_i can be determined as follows:

$$\eta_i = \frac{q}{I(t)} = h_{ew} \frac{(T_w - T_g)}{I(t)} x100 \qquad (32)$$

Where;

$I(t)$ is the amount of solar radiation within a given time interval.

3.2.5 The simplifying assumptions

Wording of certain assumptions is necessary for the system approached simulation:

- Heat transfer is dimensional.
- Heat flow is transient.
- Loss of water vapour neglected.
- Wind speed is constant.
- Thermo physical properties of materials remain constant with temperature.

3.2.6 Still/cover dimensions

- Base: 200x200 mm
- Back wall height: 105 mm
- Front wall height: 50 mm
- Glass thickness 6 mm
- Glazing Angle: 15.4˚ (55 mm rise in 200 mm)
- Reflector angle: 120˚ from glass cover
- Reflector length: 207 mm
- Reflector width: 200 mm

The glazing and reflector angles are both critical in designing. The glazing angle should be equal to latitude depending on still location because it is at this angle that the incident radiation is at right angles with the glass cover. This minimises the amount of radiation that is reflected.

The reflectors should be fixed at a 120˚ angle from the glass cover on both sides. This angle maximises reflection of solar radiation onto the still from both reflectors at solar noon. Solar noon is the time at which the sun is directly overhead the still. This is illustrated in figure 7. Angles greater than 120˚ from the glass cover reduce the reflection effect of the reflectors towards the still as shown in figure 8. On the other hand, angles less than 120˚ will reduce the reflection effect at solar noon and will also increase the shadow effect of the reflectors as shown in figure 9. Therefore a balance is to be struck between maximising reflection of solar radiation onto the still and minimising the shadow effect of the reflectors themselves (Zimmerman, 1981).

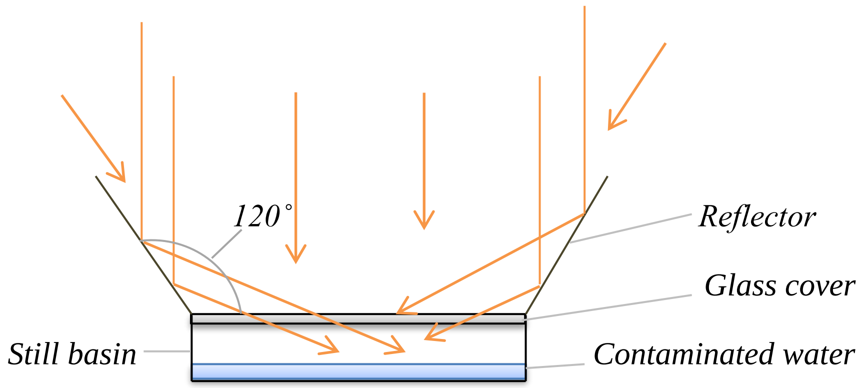

Fig 7. Radiation at solar noon with 150 mm reflectors at 120˚

Source: (Zimmerman, 1981)

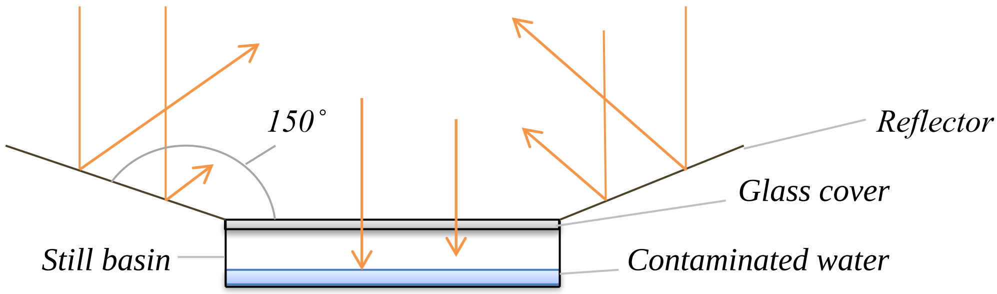

Fig 8. Radiation at solar noon with 150 mm reflectors at 150˚

Source: (Zimmerman, 1981)

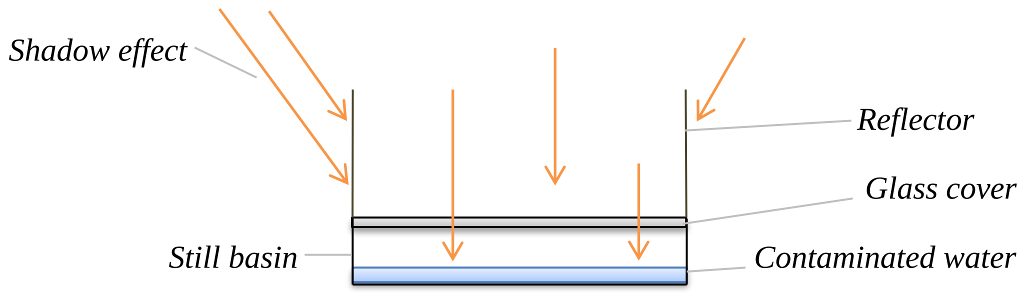

Fig 9. Radiation at solar noon with 150 mm reflectors at 90˚

Source: (Zimmerman, 1981)

The length of the glass should be 207 mm. This is the hypotenuse distance of the top layer of the still. A reflector width of 200 mm stretching along the 120˚ angle was selected as a width equal to the base width (200 mm in this case). This is the optimum width for these still design parameters providing a balance between reflector function and how much area of the reflectors is essential. A longer reflector may shadow the still and some radiation reflected off it may not even fall onto the still as shown in figure 10. A shorter reflector will result in minimal reflection effect as illustrated in figure 11 (Zimmerman, 1981).

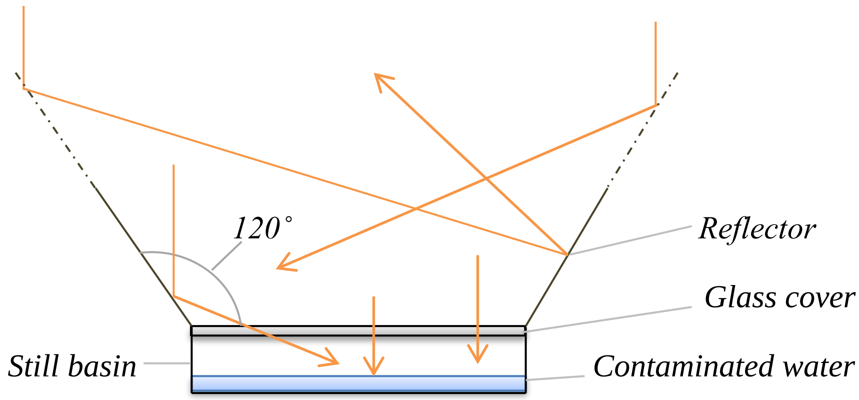

Fig 10. Radiation at solar noon with 200 mm reflectors at 120˚

Source: (Zimmerman, 1981)

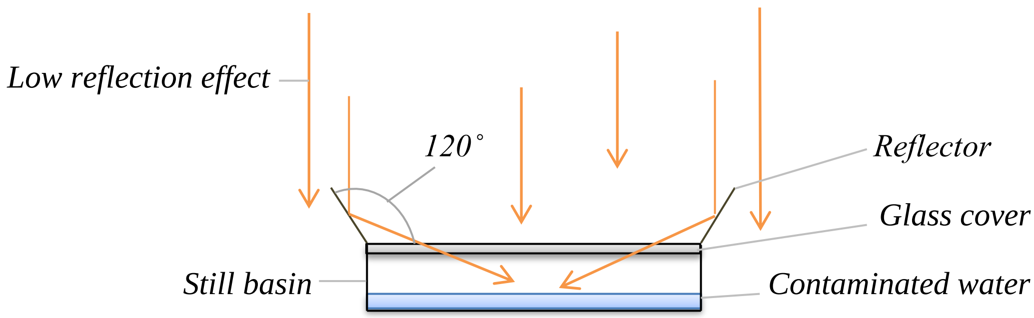

Fig 11. Radiation at solar noon with 75 mm reflectors at 120˚

Source: (Zimmerman, 1981)

3.3 APPROACHES TO ACHIEVING THE OBJECTIVES

The plan of action for this project was divided into two major parts. The first part involved theoretical investigations with analytical methods that can predict the optimum tilt angle for the glass cover and the reflectors to be used. The second part of this project involved experimental investigations with outdoor testing of the two stills. After evaluating the results of these two investigations, conclusions were made about the validity of the analytical findings, as verified by experimental evidence. Further conclusions were made about the optimum reflection and orientation of the proposed design.

Two reservoirs are to be used to supply water to the stills. One should be placed on a tripod angle iron stand and must have sufficient operating head to supply the other with water. The tank at a lower head should be placed on the ground and should have a flow control valve placed in it to limit the water level inside the stills. An angle iron frame should be fabricated in such a way that it supports the two stills and the supply reservoir. The frame on which the stills should be placed must be at a level equal to that being controlled in the reservoir having the flow control valve.

The two reservoirs are to be left open and be exposed to solar radiation to provide means of preheating the water before it enters the stills. Supply pipes should be preferably black to absorb more energy.

Two identical solar stills were fabricated using local materials. One of them has reflectors while the other does not. The stills were each filled with water volumes of 600ml in the first tests and 400ml in the second tests from the same source sample. The stills were subjected to the same conditions and various yields of distilled water produced from each still were measured daily on a 7-hour interval from 9.00hrs to 16.00hrs. A data logger was used to record the radiation and ambient temperatures during the 7-hour interval. The results were then tabulated and analysed. Samples of the distillate and raw water from the Goma Lakes were tested for various parameters and compared to World Health Organization (W.H.O) drinking water standards.

CHAPTER 4

4 RESULTS AND DISCUSSION

4.1 EXPERIMENTAL FINDINGS

The following results were obtained from the experiments conducted using solar stills with and without reflectors. Observation deductions in relation to different factors have also been presented in this chapter.

Table 4.1: Effect of still design on distillate output

Experiment No.	Distillate Output (ml)		Distillate Output Percentage increase (%)
	Still without reflectors	Still with reflectors	
1	49.8	59.1	18.7
2	54.7	68.3	24.9
3	54.0	66.4	23.0
4	56.9	69.8	22.7
5	58.4	74.2	27.0
6	59.2	76.8	29.7
7	60.4	78.7	30.3

The results depicted in table 4.1 are presented pictorially in figure 13.

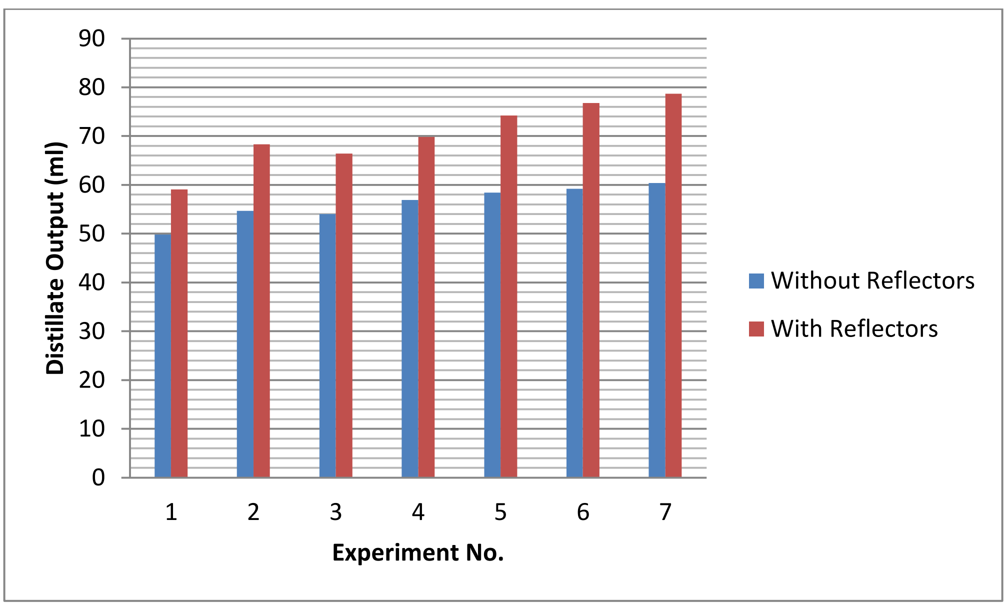

Fig 12: Histogram of solar still distillate output per experiment

Source: (Experimental tests, 2015)

Table 4.1 clearly shows that there is a substantial increment in the distillate output per day between the two different designs. Using reflectors increases the output from a range of 18% to 30%. This was largely due to the fact that more solar radiation was received by the still with reflectors. More radiation translates into more light to heat energy transformation and more heat results in increased distillate output eventually improving still performance. The variations in the percentage increments was influenced by other factors rather than still design factors and are discussed later in this chapter.

Table 4.2: Effect of solar radiation and water depth on distillate output

Experiment No.	Depth (mm)	Interval Average Radiation (W/m^2)	Distillate Output (ml)	
			Still without reflectors	Still with reflectors
1	15	622	49.8	59.1
2	15	664	54.7	68.3
3	15	626	54.0	66.4
4	15	660	56.9	69.8
5	10	564	58.4	74.2
6	10	701	59.2	76.8
7	10	700	60.4	78.7

The amount of solar radiation received by the stills greatly influenced the distillate output. For example in experiments 1 and 2 shown in table 4.2, the interval average radiation increased by 42 W/m^2. This resulted in 5ml and 9.2ml increments of distillate output for the still without reflectors and the still with reflectors respectively. This also shows that a small variation of solar radiation received by the stills results in a larger change in the distillate output between the two still designs.

The two stills each had an interior base area of $0.04m^2$. Therefore constant water volumes of 600ml and 400ml could be achieved by water depths of 15mm and 10mm respectively. This adjustment was aided by a flow control valve. The depths greatly influenced the distillate output. Experiments 4 and 5 shown in table 4.2 are at depths 15mm and 10mm respectively. Radiation of an additional 96 W/m^2 is received in experiment 4 but produces less distillate in both still design cases than in experiment 5. This is because less energy is required to evaporate relatively smaller water volumes.

Table 4.3: Effect of partial cloud cover between 10.00 to 14.00 hours on still design

Nature of Radiation	Experiment No.	Depth (mm)	Interval Average Radiation (W/m^2) (10.00 to 14.00)	Distillate Output (ml)		Distillate Output Percentage increase (%)
				Still without reflectors	Still with reflectors	
Partially clouded	1	15	680	49.8	59.1	18.7
	5	10	659	58.4	74.2	27.0
Clear sky	3	15	777	54.0	66.4	23.0
	7	10	819	60.4	78.7	30.3

The effect of radiation due to cloud cover was observed during experiments 1 and 5. An interval from 10.00 hours to 14.00 hours was analysed because this was the interval that affected the output of the still having reflectors. At a constant water depth of 15mm, interval radiations of 680 W/m^2 and 777 W/m^2 resulted in 18.7% and 23.0% distillate output increments for the two still designs respectively. This showed that partial cloud cover will greatly affect the distillate output. Cloud cover did not only reduce the amount of radiation received but reduced the reflector effect on the still designed with reflectors.

Table 4.4: Effect ambient temperature on distillate output

Experiment No.	Interval Average Ambient Temperature (°C)	Distillate Output (ml)	
		Still without reflectors	Still with reflectors
1	25.2	49.8	59.1
2	28.2	54.7	68.3
3	27.7	54.0	66.4
4	29.0	56.9	69.8

A directly proportional relationship between the ambient temperature and distillate output was observed. High solar intensities are accompanied by high ambient temperatures resulting in higher energy received from the surrounding. The overall system heat losses are reduced due to the drop in temperature gradient between the still and its surrounding.

The results depicted in table 4.4 are presented graphically in figure 14 and 15.

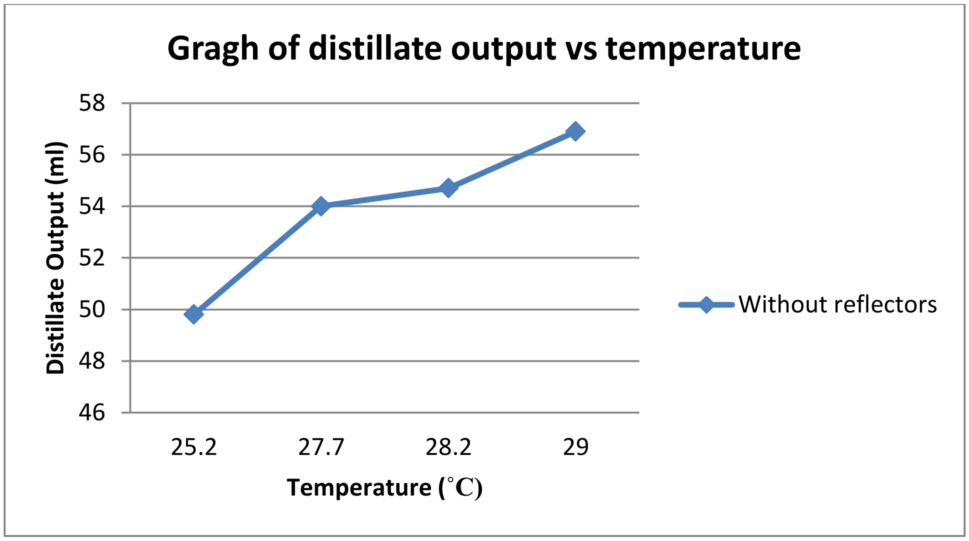

Fig 13: Graph of distillate output vs temperature (without reflectors)

Source: (Experimental tests, 2015)

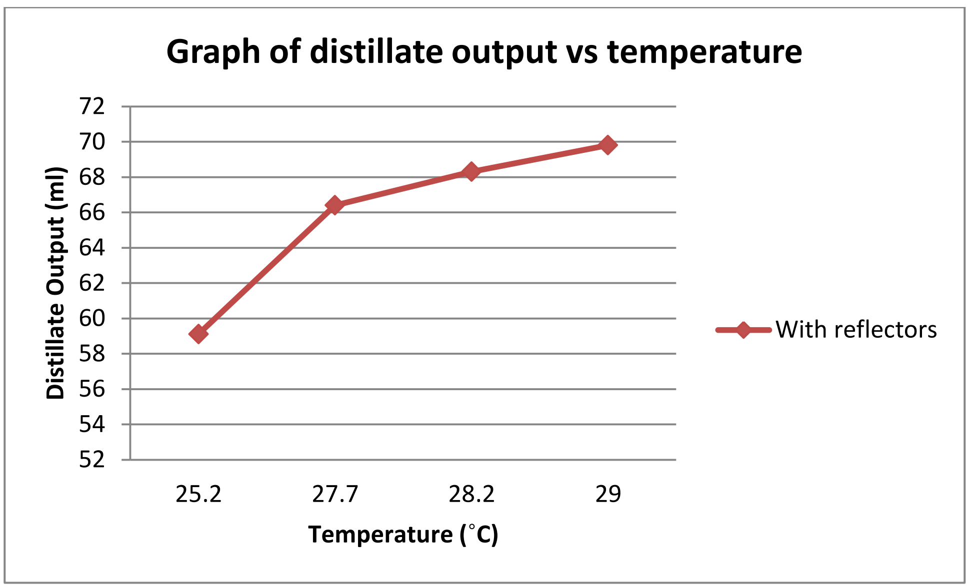

Fig 14: Graph of distillate output vs temperature (with reflectors)

Source: (Experimental tests, 2015)

Table 4.5: Water quality laboratory results

Sampling date: 04/06/2015

Testing date: 06/06/2015

Parameter	Raw water sample (Goma lakes)	Still distilled water	World Health Organization drinking water standards limit
PHYSICAL			
pH	7.63	7.7	6.5 – 8.5
Total dissolved solids (mg/l)	354	15.2	1000
Turbidity (NTU)	14.3	0.95	5
CHEMICAL			
Alkalinity ($CaCO_3$ mg/l)	204	7	500
Total Hardness ($CaCO_3$ mg/l)	284	11	500
MICROBIOLOGICAL			
Faecal Coliforms (No./100ml)	33	0	0
Total Coliforms (No./100ml)	129	0	0

A few selected water parameters were tested at the environmental engineering laboratory at the University of Zambia and compared to World Health Organization (W.H.O) drinking water standards. After making the comparisons, the water produced by the still was clearly clean and safe for drinking.

Some parameters were not tested due to financial constraints but testing for hardness for example gives us an indication that other chemicals such as nitrates or sulphates are also absent. A zero count of faecal coliforms was observed from the distilled water sample. Faecal coliforms are indicator organisms for faecal contamination of the water. Positive tests for these would mean the water possibly contains disease causing pathogens such as Escherichia coli (E. coli).

4.2 THEORETICAL AND EXPERIMENTAL RESULT COMPARISONS

The following assumptions were made in the model before the theoretical results (see appendix C) were deduced for experiment number 3:

- All physical properties of materials are not affected by temperature differences.
- Vapour-air mixture and insulation are not regarded as systems or participating media.
- The water inside the still and glass cover do not interact with incoming solar radiation.
- The solar still is a closed system.

- There are no temperature gradients across the water depth, collector pipe or glass cover.

Having made these assumptions, the distillate output was found to be 0.110 kg. The experimental distillate output for the still without reflectors was 0.054 kg. This variation would have been as a result of the different influence factors mentioned in chapter 2.

4.3 JUSTIFICATION OF USING REFLECTORS

It is clear that a still with reflectors will increase the amount of distillate produced from a solar still as compared to an identical still without reflectors. The increment is brought about simply by the additional light energy that the reflectors reflect towards the water to be distilled. To justify the use of reflectors on a still to increase the distillate output, we compare the cost of making a relatively bigger solar still having no reflectors to produce the same amount of water.

Let us assume a solar still without reflectors having a basin area of $1m^2$ can produce an average of 3L/day (i.e. $3L/m^2$/day). If the distillate amount desired was 3.9L/day for example, then a solar still equipped with reflectors will require a basin area of $1m^2$. This is because reflectors may increase distillate output by about 30%, hence, raising the distillate output from 3L/day to 3.9L/day. On the other hand, for a solar still without reflectors to produce 3.9L/day, a basin area of about $1.3m^2$ will be required. This would result in additional costs of buying more basin material, a bigger cover glass, more tank paint, a relatively stronger basin support, more insulation material and a higher fabrication labour cost. Whereas to increase the distillate output by using reflectors, only additional reflective material will be required.

This additional cost incurred on stills without reflectors would be quiet high as compared to costs incurred on buying additional reflector material if say 7-10L/day was the required amount of distillate output. The 3.9L/day used here is simply for justification purposes.

CHAPTER 5

5 CONCLUSIONS

A solar still was constructed and observed under actual environmental conditions of Lusaka, Zambia. This was made possible by applying innovative, effective, simple, and decentralized on-site water treatment systems that provided safe drinking water in a cost-effective and reliable manner.

Using reflectors did not only improve performance but also laid a foundation for further development of the technology and demonstrated its practicality. Reflectors improved performance by increasing the quantity of distillate by about 23.5% at a water depth of 15mm and about 29% at a water depth of 10mm when compared to the distillate produced from a still without reflectors. It was further concluded that the effect of using reflectors to improve still performance increases at lower water depths or smaller water volumes.

The water produced was tested and adhered to World Health Organization (W.H.O) standards that are recommended for potable water. This implied that the solar water distillation method developed would be adopted at a larger scale.

The total amount of distilled water produced from the stills depended on many factors. These were solar radiation, ambient temperature, water depth, still design, and shading between 10.00 hours to 14.00 hours. To investigate the distillate output influenced by still design factors which in this case was the use of reflectors, the experiments were conducted at the same time under the same conditions. This gave a clear picture of the still design on still performance which increased with the use of reflectors.

5.1 RECOMMENDATIONS

The following recommendations were made based on the design, fabrication and operation of the solar still with reflectors:

- Mounting an additional reflector at the back of the still interior would further improve the amount of solar radiation being received by the potentially contaminated water. These reflectors should be placed in such a way that they do not come into contact with the water.
- Increasing the slope of the glass by 15° if tests are conducted in winter and reducing by an equal magnitude in summer would increase the amount of radiation being absorbed by reducing the amount of radiation being reflected by the glass.
- Replacing ordinary aluminium sheets used as reflectors with aluminized mylar sheets. This increases the amount of radiation that is received by the water in the still.
- Lining the distilled water collecting troughs with colourless silicon sealant would help prevent them from rusting and also shield the distilled water from possible contamination from the rust that developed on the troughs during tests.

- Overall still efficiency could be further increased by lowering the depth of water to about 5mm. A lower depth further reduces the amount of heat required to make the water evaporate.
- Fabricating an identical solar still without providing preheating and low and constant depth improvements would give a clear picture of the effects of the various improvement modifications used in the design.
- Selecting a better testing location for the stills. An area that is fairly covered with vegetation to prevent dust particles that are suspended in wind from rising and falling onto the glass would also increase the efficiency.

BIBLIOGRAPHY

American Water Works Association (1998) *Standard Methods for the examination of Water and Wastewater*, Washington: APHA.

Autodesk (2009) 'Shading Design', *Environment Building Design*, May.

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

Baum, V. (1970) 'Proceedings of International Solar Energy Congress', *The Solar Still in the Deserts*, p. 426.

Chargoy, N. (1990) *Multistage, Indirectly Heated Solar Still*, Denver: University of Colorado.

Chewe, G. (2013) 'Development in Africa: Experiences of Zambia', *Journal of Human Ecology*, vol. 24, no. 3, November, pp. 175-189.

Christian, R. (1983) 'Frequency Distribution of Coliforms in Water Distribution Systems', *Applied Environmental Microbiology*, no. 45, pp. 603-609.

Cooper, P. (1973) 'Digital Simulation of Transient Solar Still Processes', *International Journal of Solar Energy*, vol. 12, pp. 313-331.

Dunkle, R. (1961) 'Proceedings of International Heat Transfer', *The Roof Type Still and a Multiple Effect Diffusion Still*, vol. 5, p. 895.

El-Sabaii, A. (2009) 'Thermal performance of a single basin solar still with PCM as a storage medium', *Applied Energy*, vol. 86, pp. 1187-1195.

Hall, M. (2005) 'Reflector Materials for Two-dimensional Systems', *Progress in Photovoltaics*, vol. 13, no. 3, pp. 217-233.

Hikmet, S. (2005) 'An experimental study on inclined solar water distillation sysems', *Desalination*, vol. 180, pp. 285-289.

International Energy Agency (2011) 'Energy for All', *Oslo Conference*, October.

Kalidasa, M.K. (2010) 'Single basin double slope still with minimum basin depth and energy storing materials', *Applied Energy*, vol. 36, pp. 514-523.

Kumar, K. (2008) 'Performance analysis of a "V" type solar still using a charcoal absorber and a boosting mirror', *Desalination*, vol. 229, pp. 217-230.

Kyocera (2009) 'Understanding Solar Electric Modules', *Kyocera Solar Energy Products*, May.

Malik, M. (1982) *Solar Distillation*, New York: Pergamon Press.

Medugu, D. (2006) 'Eliminating Microbial Contamination and Salt', *Design and Development of Solar Still*, vol. 2, pp. 203-209.

Melling, A. (1997) 'American Institute of Physics and American Chemistry Society', *Interpolation Correlations for Fluid Properties of Humid Air in the Temperature Range 100˚C to 200˚C*, vol. 26, no. 4, p. 1113.

Mfune, O. (2008) *Promoting Renewable Energy Technologies for Rural*, Lusaka.

Muafag, S. (2007) 'Effect of water depth on the performance evaluation of solar still', *Jordan Journal of Mechanical and Industrial Engineering*, vol. 1, pp. 23-29.

NASA (2009) 'NASA Surface Meteorology and Solar Energy', *Atmospheric Science Data*, February.

National Renewable Energy (2008) *Renewable Energy Basics*, National Energy Laboratory.

Nichols, A. (1993) *The Tracking Solar Cooker*, Tucson Arizona.

Regli, S.E. (2003) *Control of Drinking Water Pathogens and Disinfection Byproducts*, F. Pontius edition, New York: John Wiley & Sons, Inc.

Ronnelid, M. (2000) 'Booster Reflectors for PV Modules', *Progress in Photovoltaics*, vol. 3, no. 8, pp. 279-291.

Sanyaolu, B. (2002) 'Performance Evaluation of Natural Fibers for Snow and Sand Filter Protection', *Enviromental Pollution Health*, vol. 2, pp. 61-66.

Schaefer, W. (1992) *Public Health Engineering Lecture Note-Book*, Delft: Delft University of Technology.

Schoneveld, G. (2012) 'Early Legal and Institutional Framework in Zambia', *Review of Policy Research*, vol. 29, no. 4.

Sobsey, M. (2002) *Accelerated Health Gains from Improved Water Supply*, North Carolina: Chapel Hill Press.

Tamini, A. (1987) 'Performance of Solar Still with Reflectors and Black Dye', *International Solar and Wind Technology*, vol. 4, p. 443.

Tiwari, A. (1989) 'Transient Analysis of Solar Still in the presence of Dye', *Energy Conversion Management*, no. 29, p. 59.

Watmuff, J. (1977) 'Solar and Wind Induced External Solar Collectors', *Solar Complex*, vol. 2.

World Health Organisation (2002) 'Water, Sanitation and Health', *Protection of Human Environment*.

Zimmerman, J.C. (1981) 'Sandia National Laboratories Report', *Sun Pointing Programs and their Accuracy*, September.

APPENDICES

Appendix A: Costing

Quantity	Description	Amount (ZMW)
2	Still basin	95
1	Spray paint	23
3	Nipples, seals & nuts	60
1	Silicon sealant	17
1	6m feeder pipe	50
8	Screw lock pin	16
1	1m 1/2” steel pipe	25
2	200x210cm glass	25
1	6m angle iron	55
1	Aluminium foil	14
1	Ball valve	40
2	20L bucket	42
1	‘T’ joint	4
1	Still frame fabrication	60
		Total: 526

Appendix B: Prototype drawings

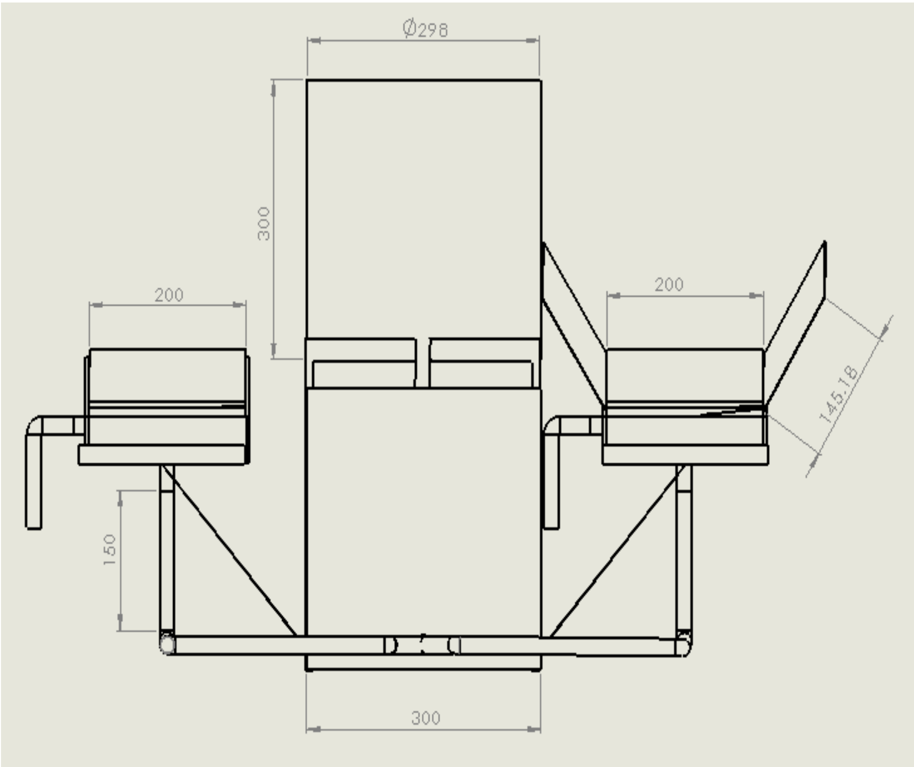

Fig 15: Design front view

Source: (SOLIDWORKS design drawings, 2015)

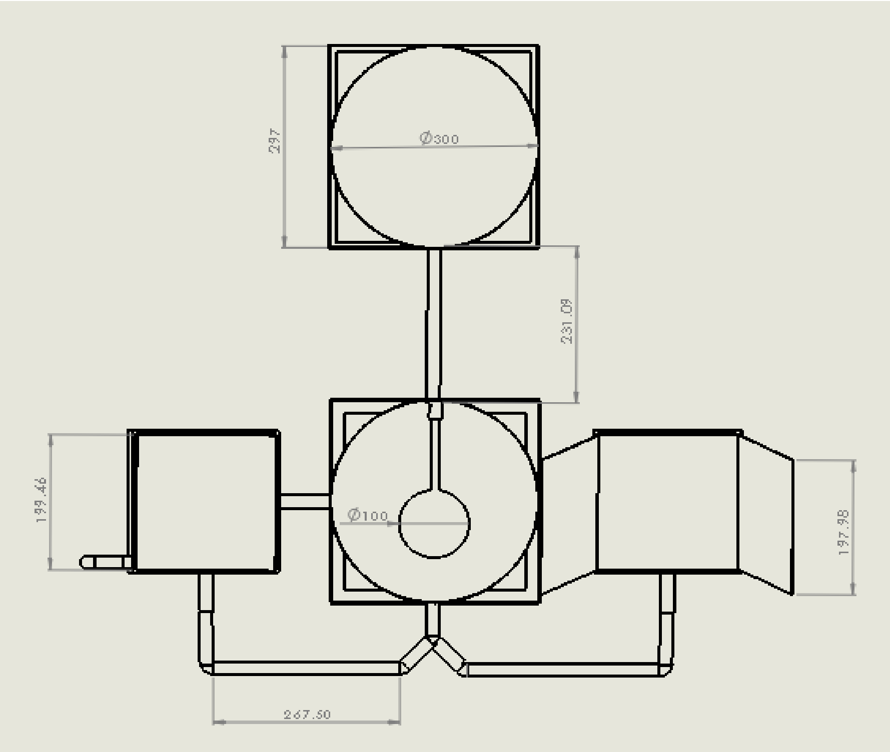

Fig 16: Design top view

Source: (SOLIDWORKS design drawings, 2015)

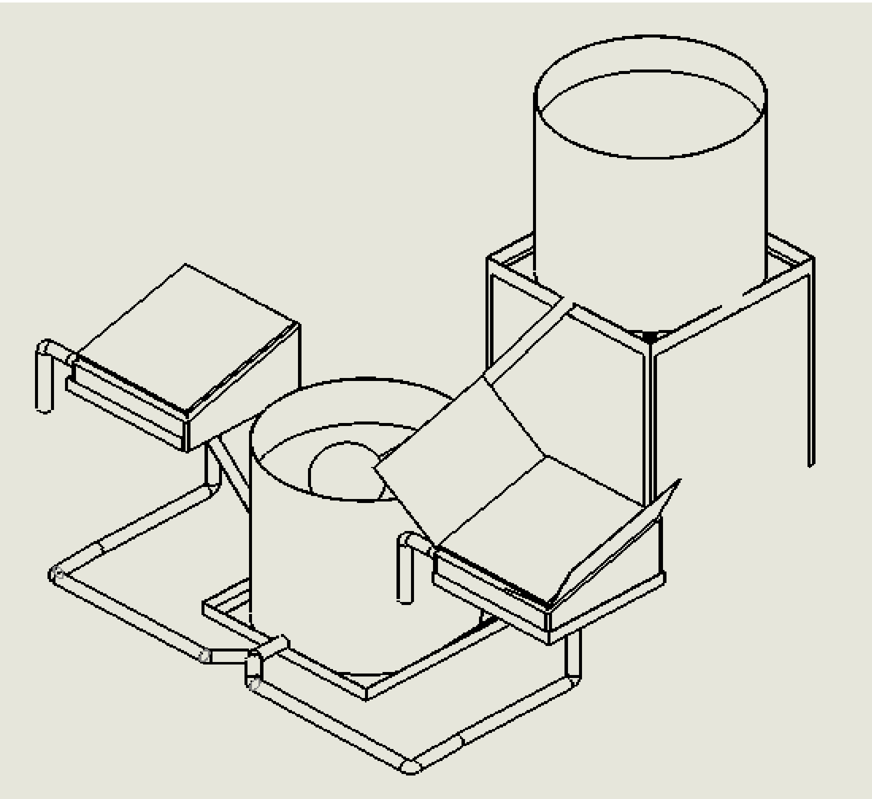

Fig 17: Design isometric view

Source: (SOLIDWORKS design drawings, 2015)

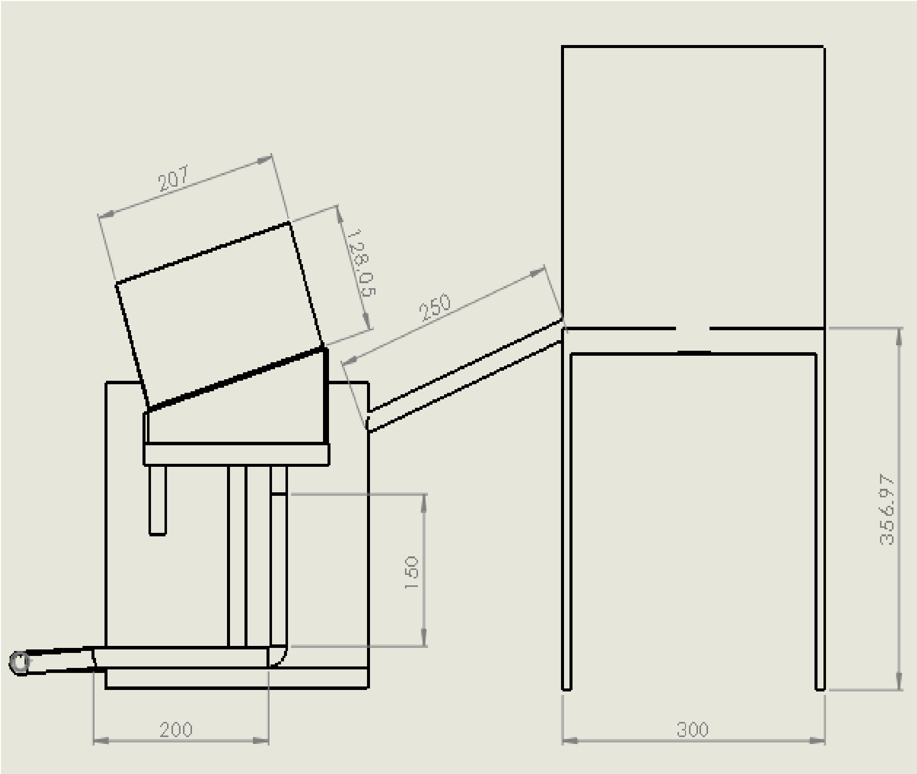

Fig 18: Design left side view

Source: (SOLIDWORKS design drawings, 2015)

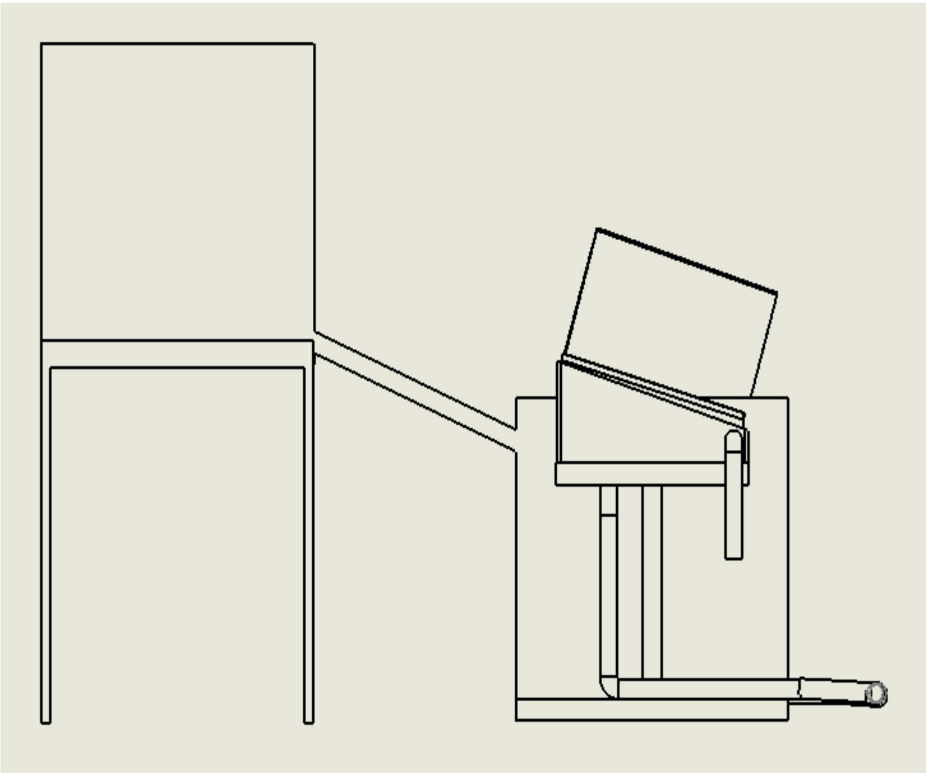

Fig 19: Design right side view

Source: (SOLIDWORKS design drawings, 2015)

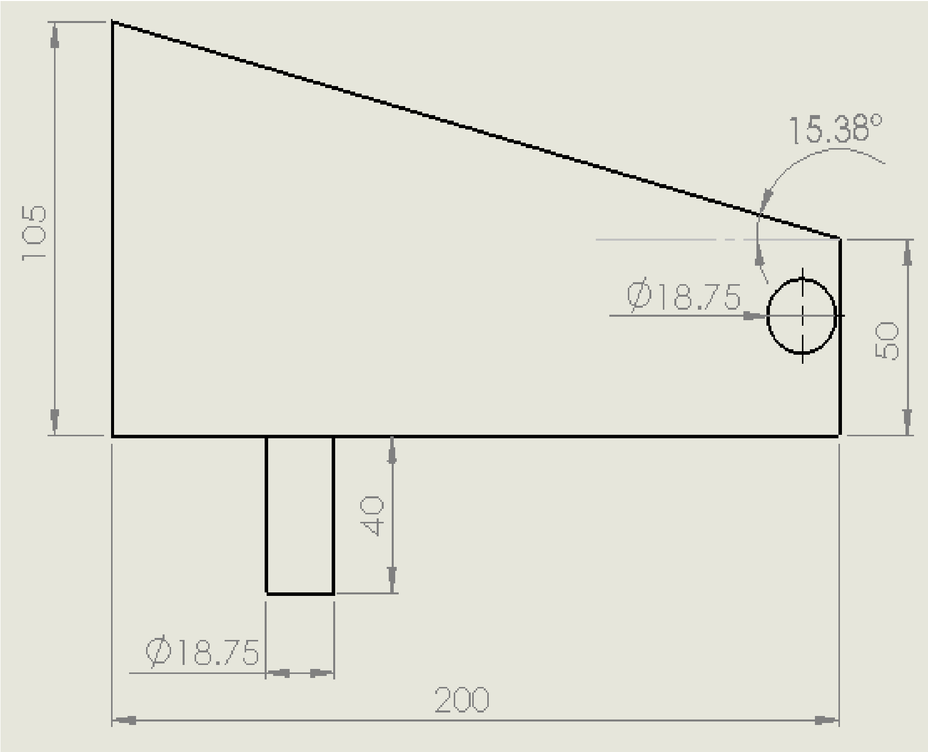

Fig 20: Design still basin left side view

Source: (SOLIDWORKS design drawings, 2015)

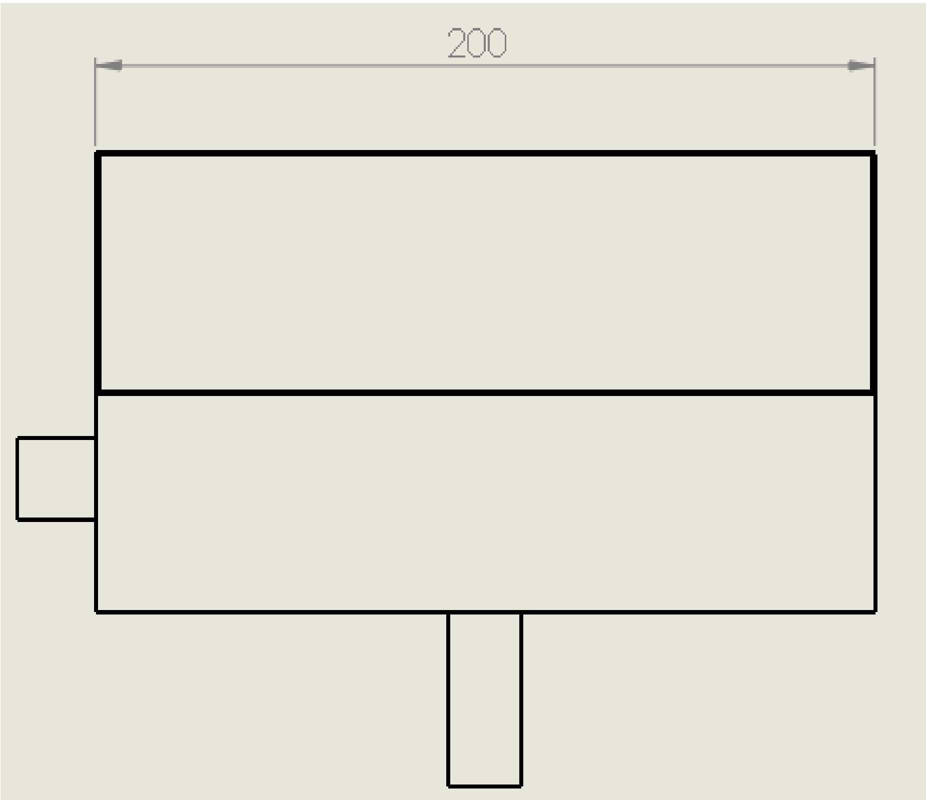

Fig 21: Design still basin front view

Source: (SOLIDWORKS design drawings, 2015)

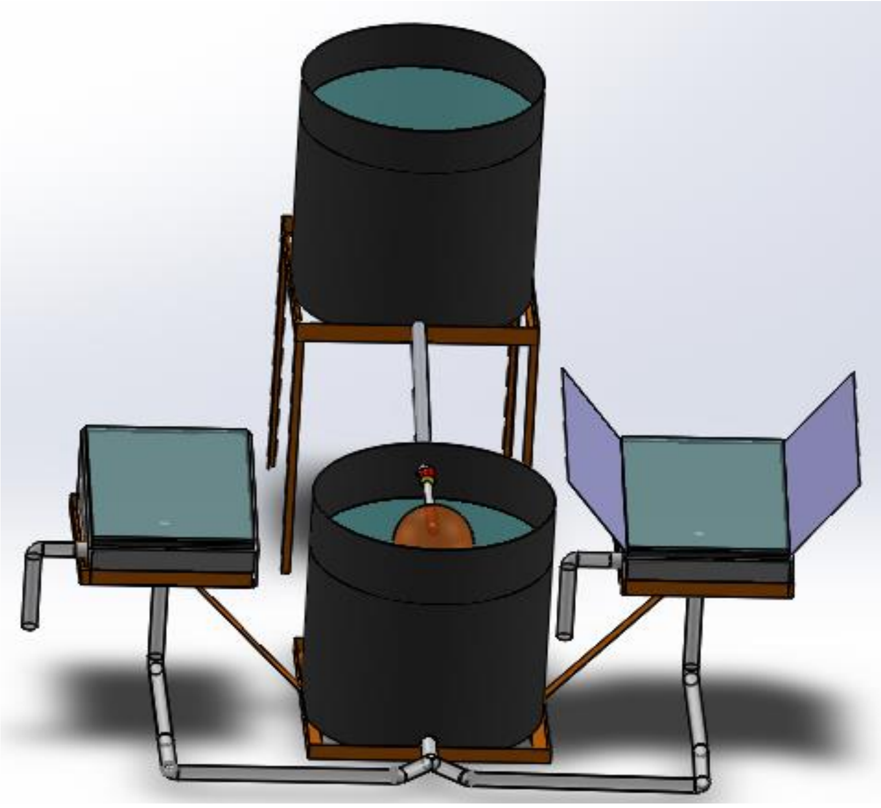

Fig 22: Design 3D front view

Source: (SOLIDWORKS design drawings, 2015)

Fig 23: Fabricated design front view

Source: (UNZA field station, 2015)

Fig 24: Weighing of distilled water sample

Source: (Agricultural engineering laboratory UNZA, 2015)

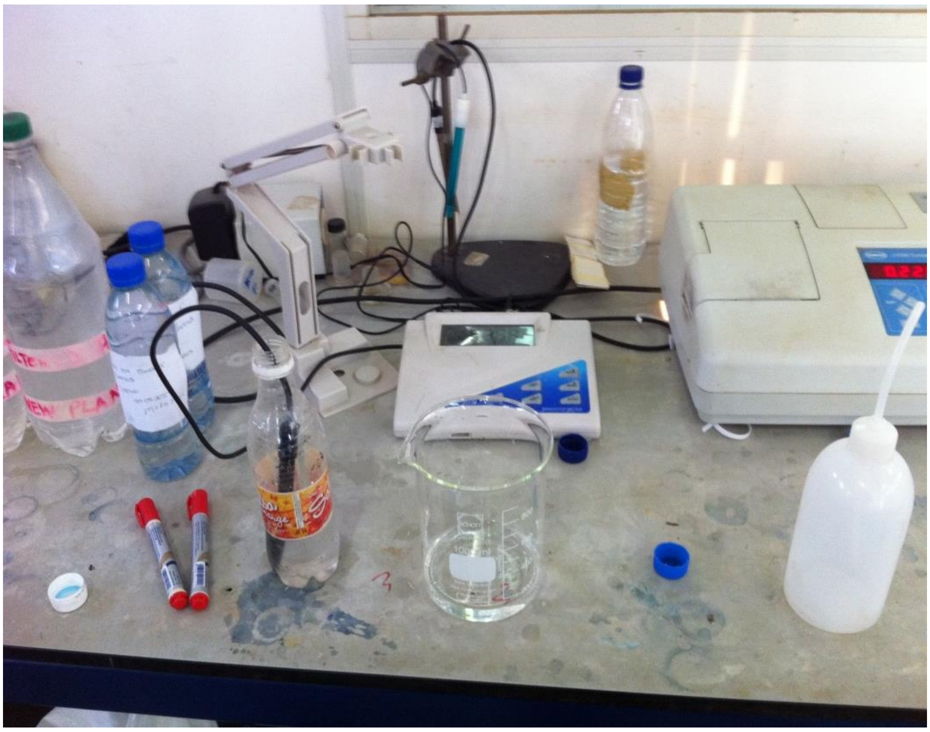

Fig 25: Water quality testing

Source: (Environmental engineering laboratory UNZA, 2015)

Appendix C: Design calculations

Analysis for experiment number 3.

Given:

Ambient temperature	300.7˚K
Glass tilt	15.4˚
Glass emittance*	0.9
Base to glass spacing	60mm
Glass temperature*	303˚K
Water temperature*	323˚K

** denotes values that have been assumed.*

Dunkle's relation:

1. Heat flux from water surface to cover by radiation, Q_r:

   $Q_r = F\sigma\,(T_w{}^4 - T_g{}^4)$

   $= 0.9*5.67*10^{-8}\,[(323)^4 - (303)^4]$

   $Q_r =$ **125.3 W/m^2**

2. Heat flux from water surface to the cover by free convection, Q_c:

   $Q_c = h_c\,(T_w - T_g)$

   The value of h_c must be obtained from empirical data, which is usually correlated using dimensionless equations of the Nusselt-Grashof type:

   $$Nu = C\,(Ra)^n = C\,(Gr.Pr)^n = \frac{h_c x}{k}$$

   $$Gr = \frac{x^3 \rho^2 g \beta \Delta T}{\mu^2}$$

   But since $\frac{1}{\nu} = \frac{\rho}{\mu}$

   $$Gr = \frac{x^3 g \beta \Delta T}{\nu^2}$$

In which x is the average glass to water spacing.

For conditions of humidity, temperature and geometry found in basin-type solar stills with glass to water spacing of 60mm, the value of Grashof's number falls in the range below:

$3.2*10^5 < Gr > 10^7$; $k = 0.075$, $n = \frac{1}{3}$

$$\frac{h_c x}{k} = 0.075\left(\frac{x^3 g\beta\Delta T}{\nu^2}\mathrm{Pr}\right)^{1/3}$$

Since $(x^3)^{1/3} = x$, this quantity can be cancelled.

Therefore, $\frac{h_c}{k} = 0.075\left(\frac{g\beta\Delta T}{\nu^2}\mathrm{Pr}\right)^{1/3}$

Mean temperature between cover and water = $\left(\frac{323 + 303}{2}\right)$

$$T_{mean} = \mathbf{313^{\circ}K}$$

Table C-1: Reference values for dry air and water vapour at ambient pressure ρ = 1 bar Source: (Melling, 1997)

Temperature (°C)	Density (kg/m^3)	Viscosity (10^{-6} kg/m s)	Therm. conductivity (10^{-3} W/m K)	Specific heat (kJ/kg K)	Prandtl number
			Dry air		
100	0.9329	21.94	31.39	1.012	0.7070
120	0.8854	22.80	32.75	1.014	0.7060
140	0.8425	23.65	34.08	1.016	0.7054
150	0.8226	24.07	34.74	1.018	0.7051
160	0.8036	24.48	35.39	1.019	0.7050
180	0.7681	25.29	36.68	1.022	0.7049
200	0.7356	26.09	37.95	1.026	0.7051
			Water vapor		
100	0.5896	12.42	25.00	2.026	1.003
120	0.5577			2.005	
140	0.5294			1.991	
150	0.5165	14.29	28.90	1.986	0.978
160	0.5040			1.983	
180	0.4812			1.979	
200	0.4604	16.26	33.30	1.979	0.959

Checking for the physical properties of air at mean temperature of 313˚K from table C-1 by interpolation, we get;

$\nu = 19.384 * 10^{-6}$ kg/m.s,

k = 0.0274 W/m.K,

Pr = 0.7093,

$\beta = 1/T_{mean} = 1/313°K = 3.12 * 10^{-3}\ K^{-1}$,

$\Delta T = 20°K$.

$$h_c = 0.075k\left(\frac{g\beta\Delta T}{\nu^2}\Pr\right)^{1/3}$$

$$= 0.075(0.0274)\left(\frac{9.81* 0.00312 * 20}{(19.384 * 10e{-}6)^2}0.7093\right)^{1/3}$$

h_c = **2.16 W/m².°K**

Therefore, $Q_c = h_c\,(T_w - T_g)$

$= 2.16 * 20$

Q_c = **43.12 W/m²**

3. Heat loss through the base and perimeter of the basin, Q_b;

<u>Bottom losses</u>

$$U_b = \left(\frac{1}{h_w} + \frac{L_g}{k_g} + \frac{1}{h_{cb}+h_{rb}}\right)^{-1}$$

$h_w = 5.7 + 3.8v$

$= 5.7 + 3.8*0.57$

$= 7.87$ W/m².°C

$h_{cb} + h_{rb} = 5.7$ W/m².°C

$$U_b = \left(\frac{1}{7.87} + \frac{0.0004}{62.3} + \frac{1}{5.7}\right)^{-1}$$

U_b = 3.31 W/m^2. ˚C

$Q_b = U_b (T_w - T_g)$

= 3.31 (50 – 30)

Q_b = **66.2 W/m^2**

<u>Side losses</u>

$$U_s = U_b \frac{A_{ss}}{A}$$

Where A_{ss}= surface in contact with water

A = area of basin

A_{ss} = 4(0.015*0.2)

= 0.012 m^2

A = 0.2*0.2

= 0.04 m^2

$$U_s = 3.31 * \frac{0.012}{0.04}$$

= 0.993 W/m^2.˚C

Q_{sides} = 0.993(50-30)

= **19.86 W/m^2**

Q_{ew} = 523.62 - 125.3 - 43.12 - (66.2 +19.86)

= **269.14 W/m^2**

The latent heat of vapourization is temperature dependent (Chargoy, 1990), and is given as:

$$L = 2.494*10^6 (1 - 9.4779*10^{-4}T_w + 1.3132*10^{-7}T_w^2 – 4.7974*10^{-9}T_w^3)$$

For T_w = 50˚C

L = 2.275MJ/kg

$m_{ew} = \frac{Q_{ew}}{L} * 3600$

$= \frac{269.14}{2.275*10^6} * 3600$

$= 0.4079$ kg/m^2.h

For a period of 6.5 hours and a condensing surface area of 0.0414m^2, we get;

$m_{ew} = 0.4079*6.5*0.0414$

= **0.110 kg** of distillate output