“DESIGN AND MANUFACTURING OF A STEPPED-SLOPED SOLAR STILL INCORPORATED WITH PHASE CHANGE MATERIAL (PCM)”

Final Year Project Report

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In Partial Fulfillment

Of the Requirements for the Degree of

Bachelors of Mechanical Engineering

By

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EXAMINATION COMMITTEE

We hereby recommend that the Final Year Project report prepared under our supervision by: **HAMZA SAQIB(05206)** and **ATTA-UR-RAZZAQ(05418)** ,Titled: **"DESIGN AND MANUFACTURING OF A STEPPED-SLOPED SOLAR STILL INCORPORATED WITH PHASE CHANGE MATERIAL (PCM)"** be accepted in partial fulfillment of the requirements for the award of **MECHANICAL ENGINEERING** degree.

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ABSTRACT

Commonly water sources contain harmful bacteria, minerals and organic impurities which make them unsuitable for drinking, irrigation and other purposes. Common process of desalination consumes large amount of energy to remove a portion of pure water from salt water. Solar still is the oldest method to convert saline and brackish water into fresh water using the unconventional source of energy which is freely and abundantly available on Earth i.e. Solar Energy. The solar still purifies water by first evaporating and then condensing it. The purified water contains no salts, minerals or organic impurities. In our Final year project, a stepped inclined solar still design is used to enhance the productivity of the conventional solar still design. The most important design parameters influencing the productivity are optimization of glass angle, absorber plate area, free surface area of water and depth of water. The stepped inclined still design is further modified by including sponges (Baffles and wick effect), PCM (2 types of Paraffin wax for latent heat storage in order to provide low light functionality of the still), external reflectors (for concentration of solar radiation on to the still), insulation (for minimizing heat loss from the base of the still), k-type thermocouples(For monitoring the temperature at various locations within the still), and bubbling effect(Integrated with fans and an external condenser in order to maximize the rate of evaporation and thus the productivity). Complete dimensioning and 2D drawing of each and every part was done using AutoCAD. 3D modelling of the project was done using Autodesk inventor. MATLAB was used to conduct a detailed numerical analysis of the project in order to determine the effect of various modifications on the productivity of the still and the corresponding comparison graphs were plotted.

ACKNOWLEDGEMENTS

"In the name of ALLAH, The most Gracious and the most merciful"

Thanks to ALLAH Almighty for blessing us with the knowledge and skills to complete our Final year project. We would like to thank our parents who helped and motivated us in each and every aspect of our project.

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FYP REPORT

ORIGINALITY REPORT

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SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Senthil Rajan, A., K. Raja, and P. Marimuthu. "Increasing the productivity of pyramid solar still augmented with biomass heat source and analytical validation using RSM", Desalination and Water Treatment, 2015. Publication	3%
2	en.wikipedia.org Internet Source	1%
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Khalifa, A.J.N.. "Effect of insulation thickness

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8	El-Samadony, Y.A.F., AS. Abdullah, and Z.M. Omara. "Experimental Study of Stepped Solar Still Integrated with Reflectors and External Condenser", Experimental Heat Transfer, 2014. Publication	1%
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12	Kabeel, A.E., Z.M. Omara, F.A. Essa, and A.S. Abdullah. "Solar still with condenser – A	<1%

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NOMENCLATURE

English Letters

A	$area$	m^2
C_p	$specific\ heat$	$\frac{J}{kgk}$
$I(t)$	$solar\ flux\ on\ an\ inclined\ collector$	W/m^2
P	$partial\ pressure$	Pa
Q	$heat\ transfer\ rate$	W
T	$temperature$	℃
dt	$time\ interval$	s
h_{fg}	$enthalpy\ of\ evaporation\ at\ T_w$	$\frac{J}{kg}$
m	$mass$	kg
m_c	$condensate$	$\frac{kg}{m^2}$
U	$side\ heat\ loss\ cofficient$	$\frac{W}{m^2k}$
V	$wind\ velocity$	$\frac{m}{s}$
rh	$relative\ humidity$	%

Greek

$\mathcal{E}$	$emissivity$	
α	$absorptivity$	
ρ	$density$	kg/m^3
β	$collector\ surface\ inclination$	$^\circ$
σ	$Stefan-Boltzmann\ constant$	$\frac{W}{m^2K^4}$

Subscripts

a	*ambient*
b	*basin*
c	*convective*
e	*evaporative*
g	*glass*
r	*radiative*
w	*water*
p	*pebble*
loss	*side loss*

CHAPTER 1

INTRODUCTION

1.1 Motivation

Fresh water is the essence of life and its scarcity is the most threatening concern for mankind. The problem is more severe in the developing countries like Pakistan where approximately 38.5 million people have no access to clean water. The unavailability of clean water is the root cause of around 1.2 million deaths each year. Among these, over 250,000 children are under the age of five who lost their life due to water-borne diseases. Majority of these cases belong to the rural areas of Pakistan. Therefore, it is highly desirable to develop an efficient, reliable, and cost effective decentralized water purification system to make the clean water accessible for remote communities.

In recent years, the population explosion has increased the demand for fresh and clean drinking water. Meanwhile the fresh water demand is rising exponentially, the industrial revolution is making the fresh water scarcity situation more alarming by polluting the lakes and rivers by industrial waste, therefore conventional sources of water are not enough to meet the current fresh water needs. However, the only water resource that is inexhaustible is the oceans. Hence a solution for sustainability may exist in low cost seawater desalination.

Therefore, the proposed project is to develop a novel solar water desalination system that is operated through solar thermal energy as the main source of energy input. One major advantage of this proposed design is its ability to have direct solar thermal heating. Subsequently, it can be located in remote and urban areas. The outcome of this project shows a significant enhancement in the Solar still performance.

1.2 Description

A solar still is based on two simple energy transfer processes namely evaporation and condensation. The processes happening within the vicinity of the still are entirely dependent on solar energy. There are many types of solar stills including large scale concentrated solar stills, and concentration trap. Basically, within a solar stills, impure water is contained outside the collector, in a storage tank. Water evaporates using energy from solar radiation. The pure water vapor condenses on the cold inside surface and drips down, where it is collected and removed for further testing.

Distillation replicates the way nature makes rain. Solar energy heats water to the point of evaporation. As the water evaporates, water vapor rises, condensing into water again as it cools and can then be collected. This process leaves impurities behind including salts, heavy metals and microbiological organisms. The end product is fresh and clean drinking water.

Conventional solar stills have low productivity and efficiency. They consist of a simple glass tank with an inclined top surface. A conventional solar still is shown in the figure below,

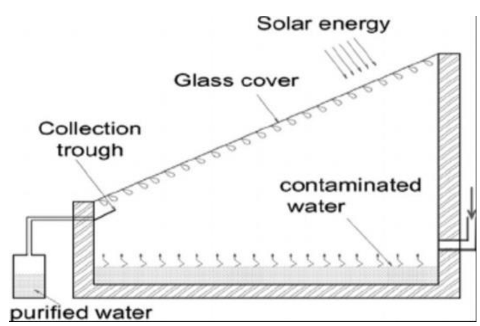

Figure 1.Conventional basin-type solar still

Owing to the low productivity of the conventional type, it is not feasible to utilize it on a large scale for water purification. This problem can be solved by modifying the conventional setup in various ways. Several different designs have been developed, but productivity still remains a problem. In our Final Year Project, we have designed and manufactured a solar still incorporating the following modifications.

- Black painted stepped-sloped (20 degrees) tray arrangement.
- Sponges (Baffles and wick effect).
- Aluminum fins.
- Phase change material (PCM-Paraffin wax).
- Air bubbling mechanism.
- External condenser.
- External reflectors.
- Different layers of insulation (glass wool, packing material and saw dust).
- K-type thermocouples.
- Top glass thickness (3mm) and inclination angle (33.7 degrees) equal to Islamabad's local latitude.

CHAPTER2

LITERATURE REVIEW

Researchers around the globe have worked intensively on different solar still designs. Several modifications have been implemented and studied thoroughly. In this section, a brief description of some previous work in the world of solar stills is presented.

2.1 Incorporation of Sponges

Bassam A/K Abu-Hijleh et al. [1] investigated the performance of a solar still with different size sponge cubes placed in the basin. The increase in fresh water output ranged from 18% to 273% compared to identical stills without sponges under identical working conditions. Their study proved that the daily output can be improved by incorporating sponges.

2.2 Incorporation of Fins

V. velmurugan et al. [2] incorporated fins in the solar still basin, due to which the production rate accelerated. Exposure area was further increased by utilizing sponges. The results were compared with ordinary basin type still. It was found that 15.3% productivity increased when sponges were used and 45.5% increased when fins were used.

Sadhana* et al. [3] made an effort to investigate the performance of finned basin solar still. In order to obtain a fair comparison, they fabricated two similar double sloped solar stills. The absorbing plate of one of the solar stills is incorporated with fins in order to enhance the heat transfer rate from the basin liner to water, while another still base is flat. It was proved that the daily output of clean water from the finned basin solar still is 18% more than the conventional double slope solar still.

2.3 Incorporation of a Stepped-Sloped configuration

A. Alaudeen et al. [4] in their work, used a stepped solar still to enhance the productivity of the conventional still. They integrated the stepped configuration with inclined flat plate collector. The setup consists of subsequent trays and flat plate collectors. This modification increases the exposure area which enhances the rate of evaporation. A conventional still was also fabricated so as to have a fair comparison between the two setups side by side. Both theoretical analysis as well as experimental analysis were conducted and the efficiency of the modified setup was compared with the conventional one. The daily efficiency of the conventional setup was determined to be lie in the range from 1% - 10%, whereas the efficiency of the stepped basin solar still was determined to be up to 16%.

A.E. Kabeel et al. [5] used a stepped basin in their study to enhance the productivity of the conventional solar still. Analysis is carried out on two different solar stills side by side and both use saline water. A conventional solar still is compared with a modified stepped solar still. The analysis showed that the productivity of the modified solar still also varies with the tray width and depth. The results concluded that the efficiency of the modified stepped solar still is 57.3% higher than the conventional design.

Neha Khare et al. [6] made an attempt to improve the productivity and efficiency of a single slope solar still by constructing a modified stepped basin still. Experimental setup was fabricated and readings were taken. Overall productivity improved drastically with upto 6 litres of output per day. The energy efficiency proved out to be as high as 60%.

2.4 Incorporation of Phase Change Material (PCM)

The output of clean water obtained per square meter area of the conventional solar still is very low. Kantesh.D.C [7] carried out a study to determine the effect of the use of phase change materials in a solar still and thus to enhance the productivity and efficiency of the conventional type. Bitumen was used as the phase change material in this analysis which basically acts to store the solar thermal energy in the form of latent heat, so that heat can obtained for night time functionality of the solar still. The efficiency of the still without the phase change material was about 25.19% and by using bitumen as the phase change material it increased to 27%.

Ashish Kumar et al. [8] investigated the performance of a single basin double slope solar still in conjunction with a phase change material (PCM). Paraffin wax was used as the thermal energy storage medium under the liner of the basin. Overall 61% gain was recorded when Phase change material was used, where as a 34% nocturnal and 64% gain in the day time output productivity was recorded, which is a drastic improvement.

2.5 Incorporation of an External Condenser

Y.A.F. El-Samadony et al. [9] carried out an experimental study on a modified stepped solar still with internal and external reflectors and an external condenser. Results were obtained with external condenser alone as well as with the reflectors. A detailed comparison between the modified-stepped solar still and the conventional setup was conducted. It was determined that the productivity of the modified still with the external condenser alone was 66% higher than that of the conventional solar still.

Narayen Pandey et al. [10] conducted an experimental study in order to determine the effect of a separate condenser on the performance of a single slope solar still. They carried out a complete comparative study between a conventional solar still and one with a separate condenser. Their results showed that the basin type solar still with separate condenser was 19% more efficient as compared to the conventional type.

A.E. Kabeel et al. [11] investigated the design modification of a single basin solar still to improve the solar still performance through increasing the productivity of distilled water. Efforts were made to improve the daily productivity of clean water using nanofluids and also by incorporating an external condenser. The results showed that by integrating the system with an external condenser, the output water yield improves by 53.2%.

Samirkhan Malek [12] carried out extensive research work in order to determine the impact of an external condenser on the daily productivity of a passive solar still. Comparative analysis was carried out between the passive solar still and the external condenser attached to it and it was shown that the external condenser improves the daily productivity quite drastically.

2.6 Incorporation of External Reflectors

Z.M. Omara et al. [13] investigated the performance of a stepped solar still with internal and external reflectors. The reflectors act to focus the solar radiation on to the still thus increasing energy input to the still. A comparison between the modified stepped solar still and the conventional solar still is conducted. The results showed that experimentally the productivity of the modified solar still with both internal and external reflectors was 125% higher than the conventional still, while with external reflectors only, it was 88% higher than that of the conventional still.

Hiroshi Tanaka et al. [14] carried out a theoretical analysis of a basin type still with internal and external reflectors. They basically used a geometrical method to calculate the solar radiation reflected and then absorbed on the basin liner. The results proves that the use of external and internal reflectors can improve the output productivity drastically except for the summer season. The average increase in the daily productivity for the entire year was 48%.

2.7 Incorporation of Bubbling Mechanism

G.C. Pandey [15] studied the effect of bubbling of ambient air and that of simultaneous air bubbling and cooling the glass cover. Bubbling of ambient helps to increase the rate of evaporation, thus increasing both the productivity and the efficiency. The results obtained were compared with the conventional solar still. It was found out that by bubbling ambient air, the fresh water output increased by 33.5%.

2.8 Incorporation of Different Layers of Insulation

To achieve a high solar still productivity and efficiency, heat losses from the sides and base of the still should be minimized in order to make sure that the absorbed thermal energy is stored. Abdul Jabbar N Khalifa et al. [16] studied the effect of insulation on the daily productivity of a basin type solar still.It was determined that the insulation thickness has a significant impact on the productivity of the still upto a thickness of 60mm. The insulation thickness could influence the productivity of the still by over 80%.

2.9 Glass Inclination Angle

A.A. Azooz et al. [17] carried out an experimental analysis on ten different solar stills with different glass inclination angles ranging from 10 degrees to 55 degrees in increments of 5. The results showed that angles between 30 degrees and 35 degrees give the least daily productivity, while those between 20 degrees and 25 degrees give the maximum (optimum) daily productivity.

CHAPTER3

METHODOLOGY

In the previous section, different types of solar still modifications and their respective effects on the productivity of clean water were analyzed. In our work, we incorporated all these modification in a single setup, which has never been done before. The main parts of our setup and their functions are presented in this section

3.1 Storage Tank (Feed water tank)

- A pair of **External reflectors** will focus the solar radiation on to the feed water tank, hence maximizing the **thermal energy** input in to the tank.
- This tank will not only store **brackish** and **saline** water, but it will also act as a **secondary solar still** with an inclined glass top surface just like the main still.
- A fraction of water in the storage tank will **evaporate** by absorbing the necessary **thermal energy from sunlight**. The water vapors will **condense** on the top and side glass surfaces of the tank. The distillate will be collected in a measuring cylinder attached to the tank.
- This tank also incorporates **Phase change material (PCM-Paraffin wax)** below the basin, which will act as a medium to store thermal energy as latent heat in order to provide low light functionality of the still.
- The base of the tank is adequately **insulated** using glass wool in order to prevent heat losses.
- A **K-type thermocouple** installed within this tank will continuously monitor the temperature of the water.

- The tank is properly **sealed** from all sides and is made **leak proof** using **Silicone gel**.
- All the stated modifications in the storage will ensure maximum productivity of clean water from it.

3.2 Connecting Pipe

- A fraction of impure water will be carried from the storage tank to the main still via a **stainless steel connecting pipe.**
- This pipe incorporates a **manually operated valve** in order to control the **flow rate** of water as it flows from the storage tank to the main still.
- All the connection associated with this pipe are properly **sealed** in order to prevent any **leakages.**

3.3 Main Still (stepped-sloped)

- A pair of **External reflectors** will focus the solar radiation on to the main still, hence maximizing the **thermal energy** input in to the still.
- The trays are configured in a **stepped-sloped manner**. There is an alternating arrangement of straight and inclined **(20 degrees inclination angle)** trays.
- A **Clear glass cover** with a **33.7 degrees** tilt angle is chosen and it will face south because the southern side receives the maximum amount of sunlight.
- The stepped-sloped tray configuration is supported on a system of **multiple threaded steel rods** in the still for **load distribution.**
- The tray configuration is **painted black** to maximize the absorption of thermal energy from sunlight as black surfaces are good absorbers and emitters.

- Two types of **paraffin wax** are incorporated as phase change material **(PCM)** below the basin to act as thermal heat storage medium. This would provide effective night time functionality of the setup. The two grades mainly differ in their melting point temperatures.
- The base of the still is properly insulated by using a combination of different **insulation** materials including **saw dust** and **packing material**. This will prevent heat loss from the base of the still.
- The trays incorporate **sponges** that act like **baffle plates** so that water remains in the tray for a longer period of time (it takes more time for water to pass through the tray) plus they also act like **wicks** i.e. they absorb water and increase surface area for evaporation.
- The inclined trays **incorporate black painted aluminum fins** which enhance the surface area for heat transfer and act as barriers to slow down the flow rate of water as it flows through the still.
- The last tray incorporates a perforated pipe for **bubbling action**. A blower will be used to **blow hot air** into this tray via the pipe. Bubbling greatly increases the rate of evaporation hence offering a substantial increase in the still productivity. The bubbling mechanism is integrated with an external condenser.
- Water will enter the main still in a distributed and uniform manner via a **perforated pipe.**
- Excess impure water from the main still is pumped via a motor back to the storage tank for heat recovery.
- Water will **evaporate** from the main still by absorbing the necessary **thermal energy from sunlight**. The bubbling action will further enhance the rate of evaporation from the still. Part of the water vapors will condense on the top and sides of the still. The distillate will collect in a graduated beaker attached to the still. Majority of the water vapors will be

sucked by a pair of fans located in a duct at the top back acrylic wall of the still. These vapors will condense via the external condenser.

3.4 External Condenser

- The condenser contains a **coiled copper pipe** to enhance heat transfer area from the vapors to the chilled cooling medium (water).
- As vapors flow through the **copper tubing**, they lose heat to the cooling medium and condense into pure liquid water. The distillate is collected in a graduated beaker attached at the outlet of the **heat exchanger.**
- The condenser contains inlet and outlet to replace the **cooling medium** from time to time.
- The outer surface of the condenser is adequately insulated using **glass wool** to reduce heat losses.

3.5 Design

Inventor was used for 3D modelling of our setup and to generate 2D views as well. This section presents 3D and 2D images of the main parts of our experimental setup.

3.5.1 Main Assembly

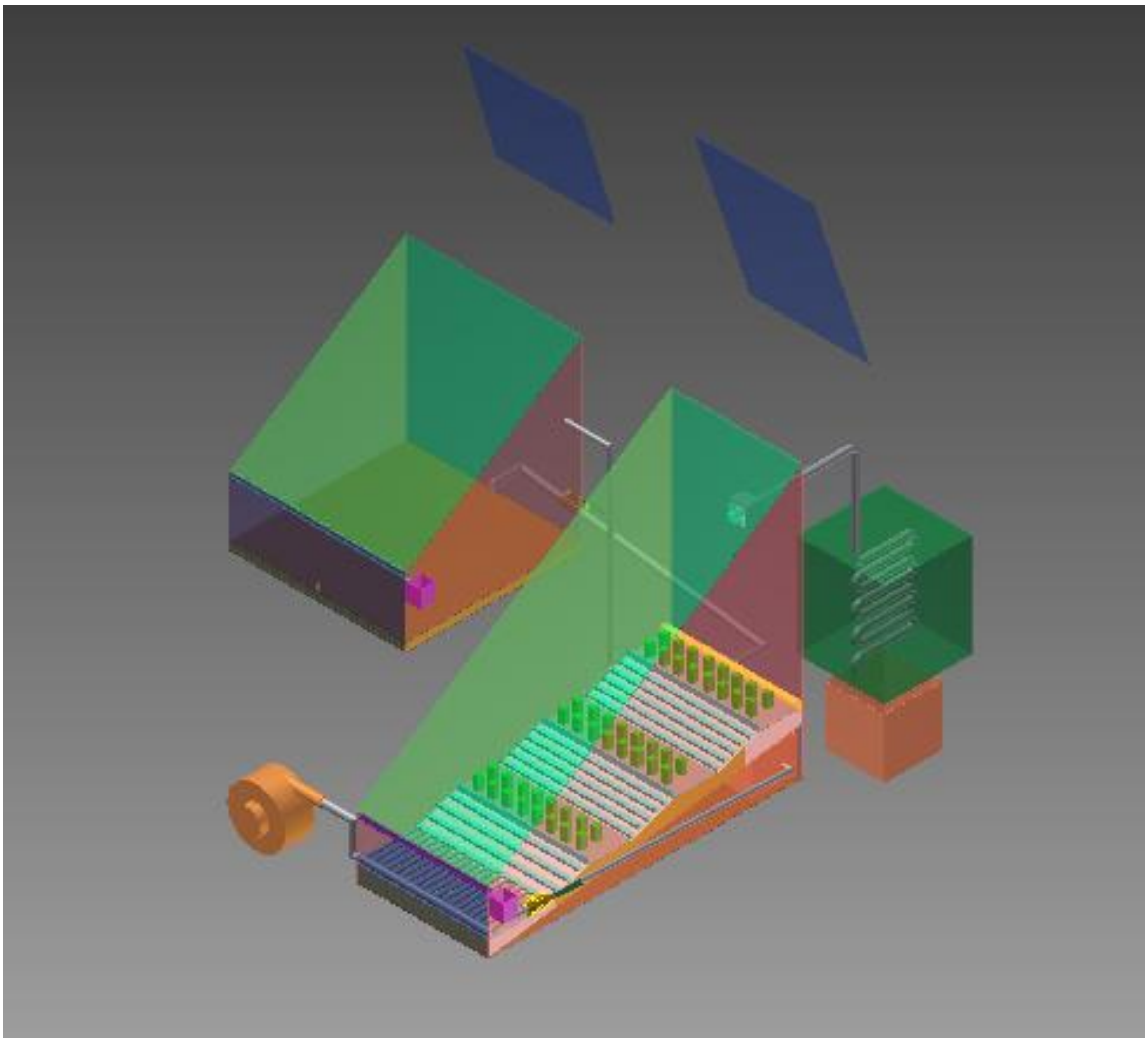

Figure 2. 3D model of the main assembly on Autodesk Inventor

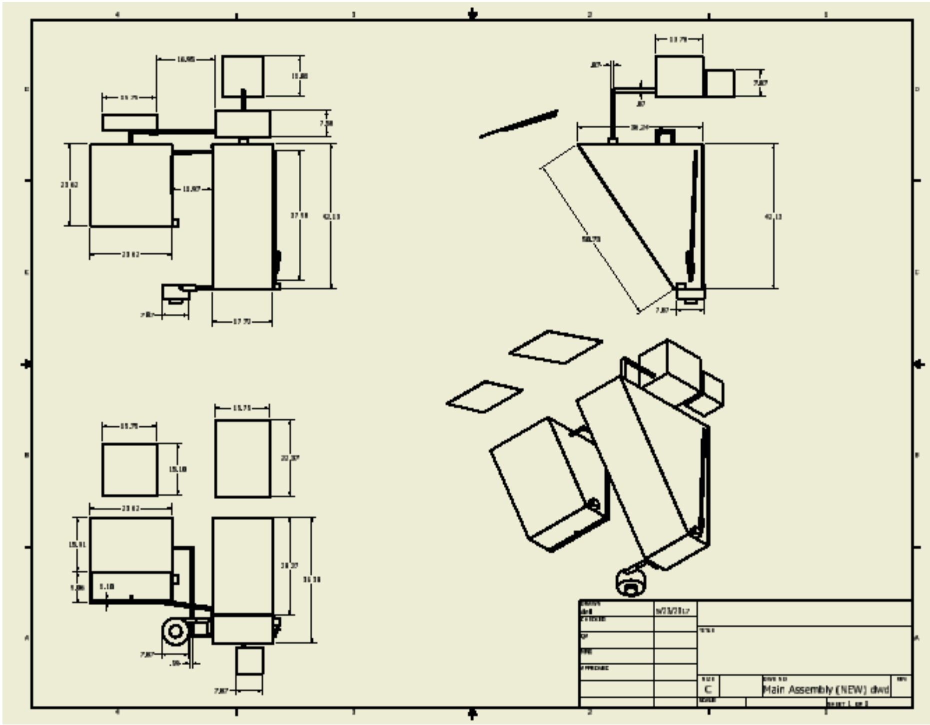

Figure 3. 2D views of the main assembly generated from Autodesk Inventor

3.5.2 Tray Assembly

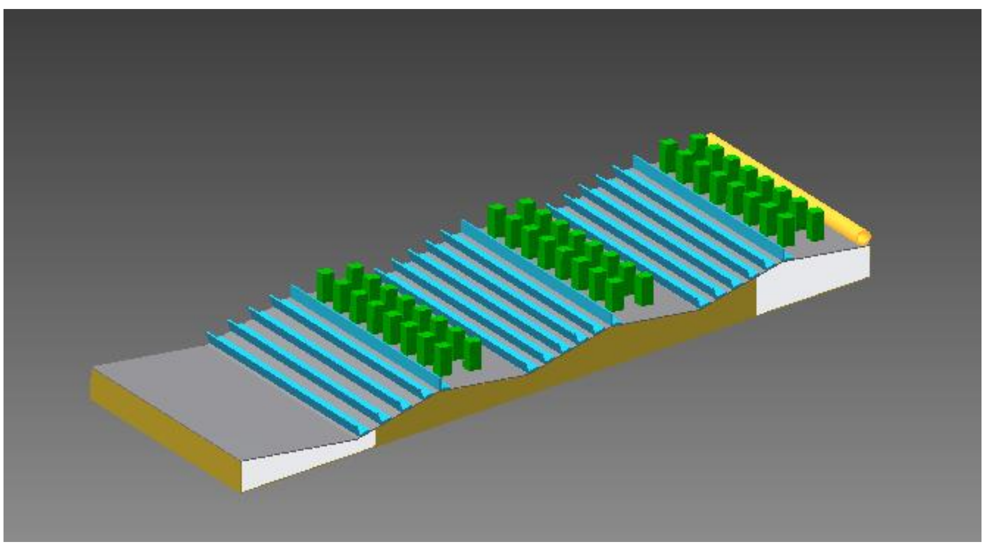

Figure 4. 3D model of the tray assembly generated on Autodesk Inventor

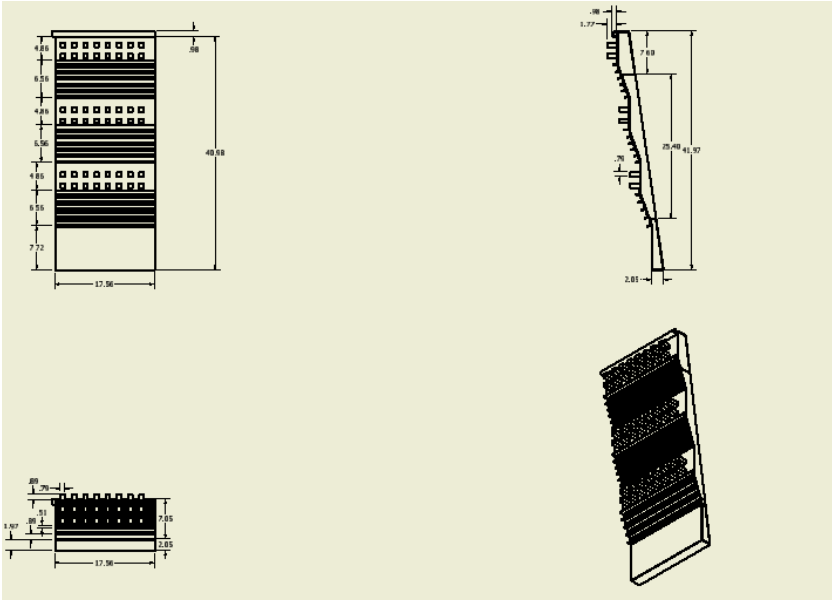

Figure 5. 2D views of the tray assembly generated from Autodesk Inventor

3.5.3 External Condenser

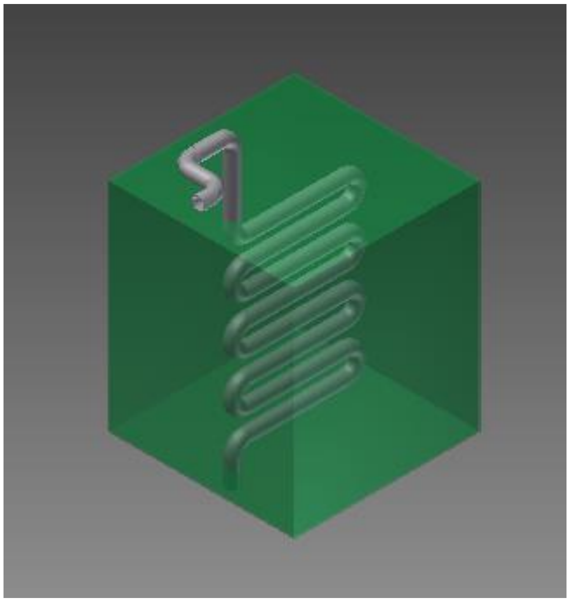

Figure 6. 3D model of the external condenser

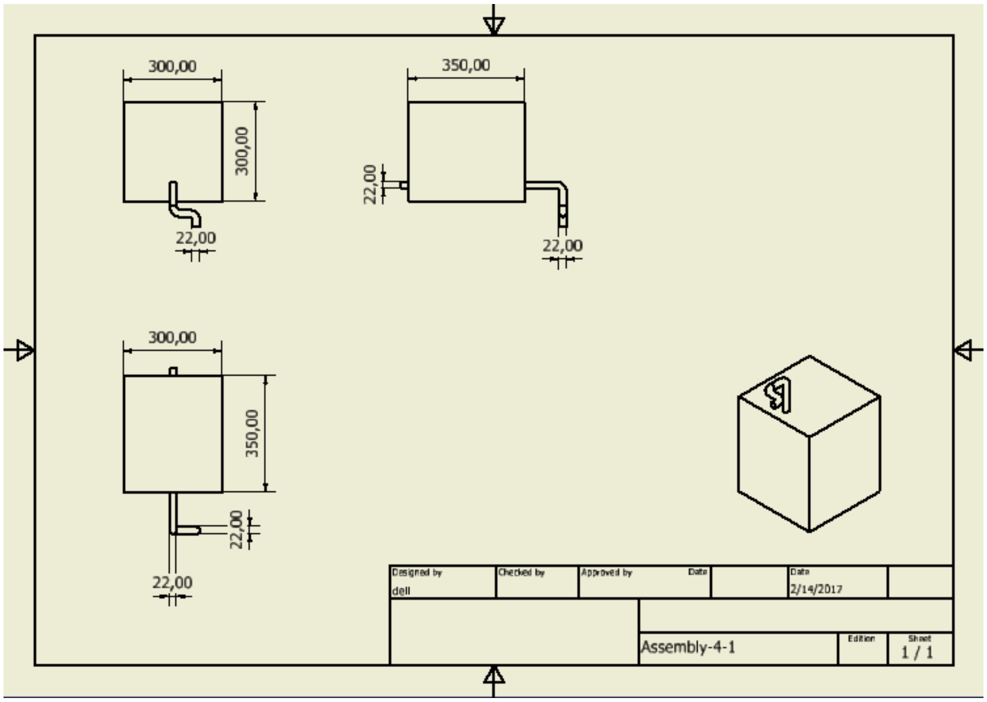

Figure 7. 2D views of the external condenser generated from Autodesk Inventor

3.5.4 Storage Tank

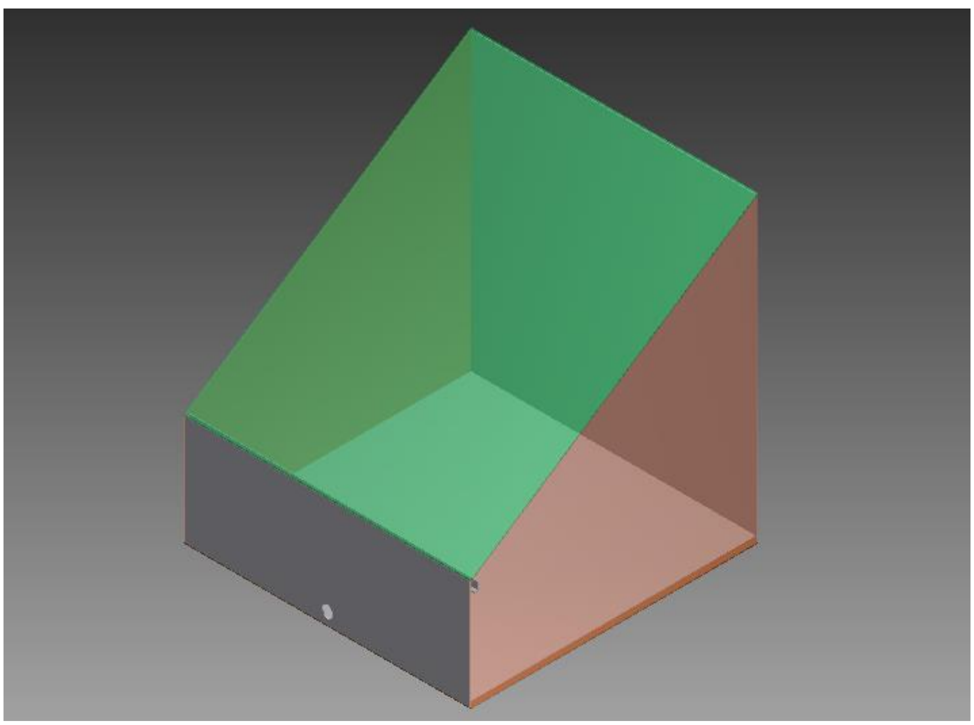

Figure 8. 3D model of the storage tank on Autodesk Inventor

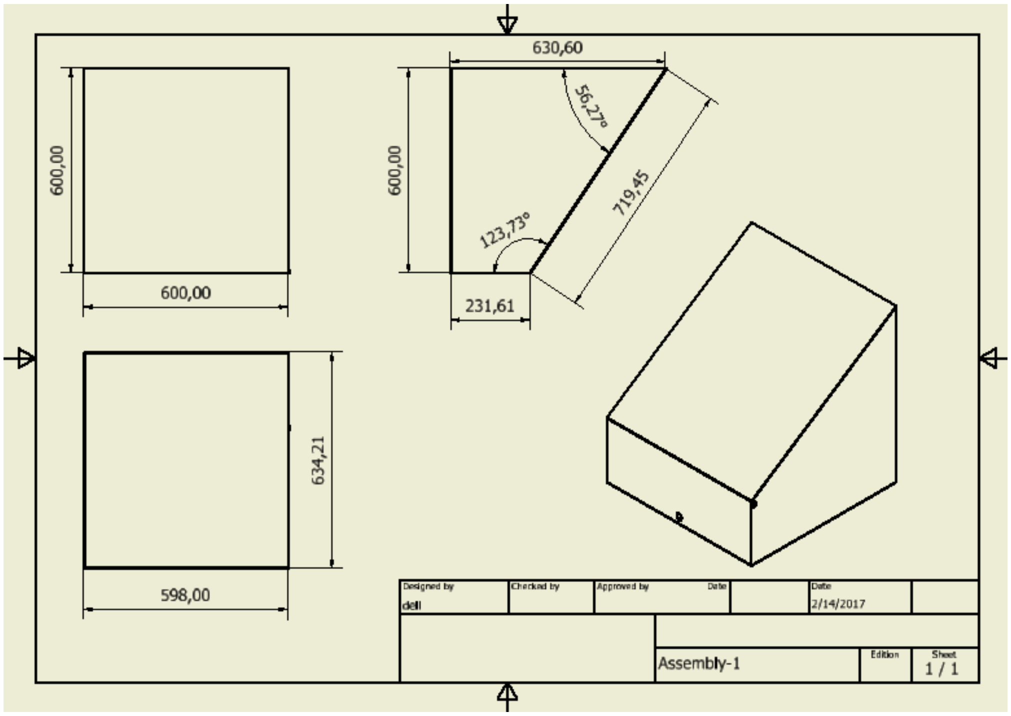

Figure 9. 2D views of the storage tank generated on Autodesk Inventor

3.5.5 Main Still

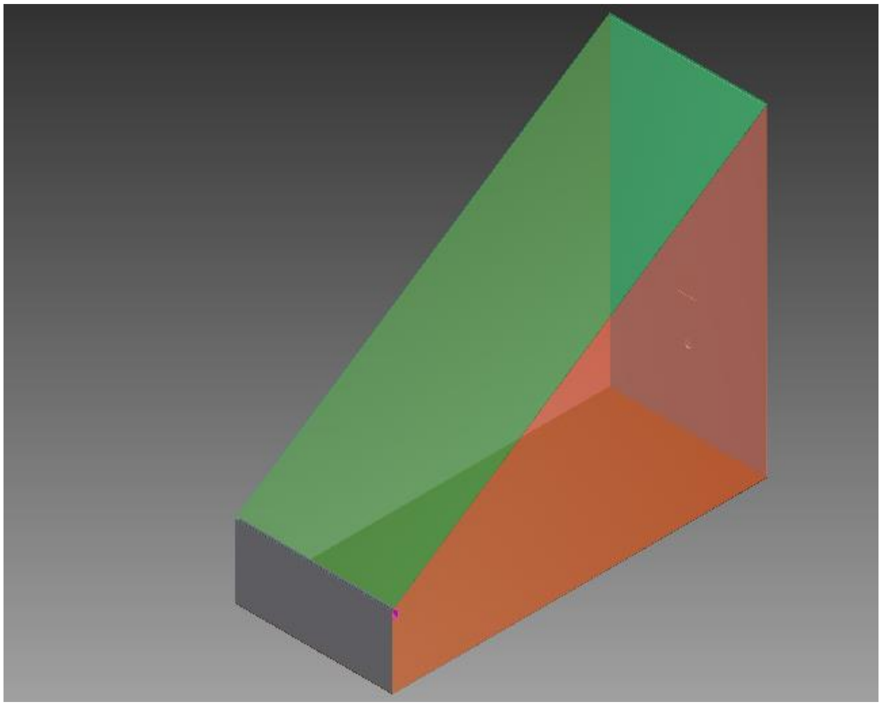

Figure 10. 3D model of the main still on Autodesk Inventor

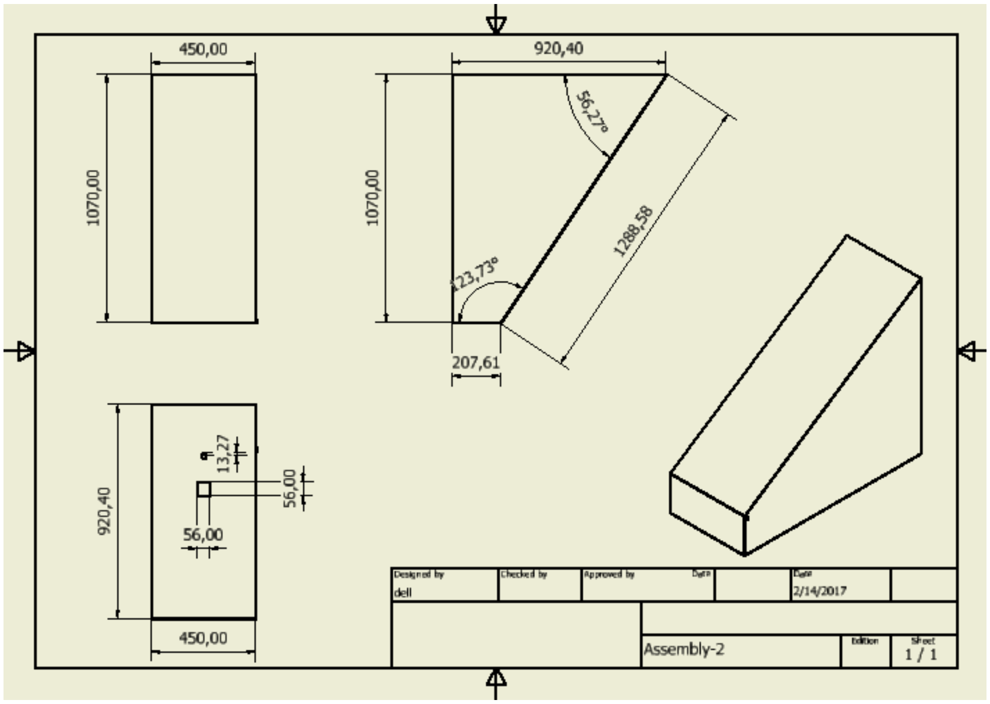

Figure 11. 2D views of the main still generated from Autodesk Inventor

CHAPTER 4

NUMERICAL ANALYSIS

The numerical analysis of both conventional solar still and stepped inclined solar still was performed to find out the productivity and daily efficiency of the solar still with different modifications such as: Stepped-sloped configuration with 20 degree slope angle, Phase change material (PCM), Sponges, External reflectors, Air bubbling action, Aluminum fins, Different layers of insulation and External condenser. Numerous different energy balance equations were solved using an iterative procedure in MATLAB. The various equations used for numerical analysis and the iterative procedure are mentioned in this context.

4.1 Stepped Inclined Solar Still governing equations

Energy received by the black surface is given by the equation,

$$I(\mathrm{t}) A_{\mathrm{b}} \alpha_{\mathrm{b}} = m_{\mathrm{b}} C_{\mathrm{p,b}} \left(\frac{\mathrm{dT_b}}{\mathrm{dt}}\right) + Q_{\mathrm{c,b\text{-}w}} + Q_{\mathrm{loss}} \qquad (1)$$

Energy received by the brackish water in the still (from sun and base) is equal to the summation of energy lost by convective heat transfer between water and glass, radiative heat transfer between water and glass, evaporative heat transfer between water and glass and energy gained by the brackish water. It's given by the equation,

$$I(\mathrm{t}) \alpha_{\mathrm{w}} A_{\mathrm{w}} + Q_{\mathrm{c,\ b\text{-}w}} = Q_{\mathrm{c,w\text{-}g}} + Q_{\mathrm{r,w\text{-}g}} + Q_{\mathrm{e,w\text{-}g}} + m_{\mathrm{w}} C_{\mathrm{p,w}} \left(\frac{\mathrm{dT_w}}{\mathrm{dt}}\right) \qquad (2)$$

Energy gained by the glass cover (from sun and convective, radiative and evaporative heat transfer from water to glass) is equal to the summation of energy lost by radiative and convective heat transfer between glass and sky, and energy gained by glass. It's given by the equation,

$$I(\mathrm{t})\alpha_{\mathrm{g}}A_{\mathrm{g}} + Q_{\mathrm{c,w\text{-}g}} + Q_{\mathrm{r,w\text{-}g}} + Q_{\mathrm{e,w\text{-}g}} = Q_{\mathrm{r,g\text{-}sky}} + Q_{\mathrm{c,g\text{-}sky}} + m_{\mathrm{g}}C_{\mathrm{p,g}}\left(\frac{\mathrm{dT_g}}{\mathrm{dt}}\right) \quad (3)$$

In the first iteration, water temperature, glass temperature and plate temperature are taken as ambient temperature and the increase in basin temperature (dTb), brackish water temperature (dTw) and glass temperature (dTg) is computed for every time interval (dt) of 5 s by solving Eqs (1-3) respectively. For evaluating, the above said temperatures in the simulation, the experimentally measured values of solar radiation, wind velocity and ambient temperature of the corresponding day and hour are used. This iteration is performed for total duration from 9 am to 7pm of a day.

Constant level of water is maintained in the stepped solar still by adding water equivalent to the condensate (mc) in every half an hour. The area of basin (Ab), the area of brackish water (Aw), the area of glass (Ag) and the Mass of the glass (mg) are calculated. The absorptivity of the still $\propto_b$ is taken as 0.92. The absorptivity of the water, $\propto_w$and absorptivity of the glass, α_g are taken as 0.05.The specific heat of the brackish water, Cp, w is 4185.5J/Kg*k.

For the next time step the parameters are redefined as,

$$T_{\mathrm{w}} = T_{\mathrm{w}} + \mathrm{dT_w} \quad (4)$$

$$T_{\mathrm{g}} = T_{\mathrm{g}} + \mathrm{dT_g} \quad (5)$$

$$T_{\mathrm{b}} = T_{\mathrm{b}} + \mathrm{dT_b} \quad (6)$$

The total condensation rate is given by the equation,

$$\frac{dm_c}{dt} = \frac{h_{e,w\text{-}g}(T_w - T_g)}{h_{fg}} \quad (7)$$

The convective heat transfer coefficient between basin and water is given by the equation,

$$Q_{c,\ b\text{-}w} = h_{c,\ b\text{-}w} A_b (T_b - T_w) \quad (8)$$

The convective heat transfer co-efficient between basin and water, hc,b-w is taken as 135 W/m2 K. The heat loss from basin to ambient is calculated from the equation,

$$Q_{loss} = U_b A_b (T_b - T_a) \quad (9)$$

Where U_b is taken as, 14 W/m^2K

The convective heat transfer between water and glass is given by the equation,

$$Q_{c,w\text{-}g} = h_{c,w\text{-}g} A_w (T_w - T_g) \quad (10)$$

Where the convective heat transfer co-efficient between water and glass is given by the equation,

$$h_{c,w\text{-}g} = 0.884 \left\{ (T_w - T_g) + \frac{[P_w - P_g][T_w + 273.15]}{[268.9 \times 10^3 - P_w]} \right\}^{1/3} \quad (11)$$

The radiative heat transfer between water and glass is determined by the equation,

$$Q_{r,w\text{-}g} = h_{r,w\text{-}g} A_w (T_w - T_g) \quad (12)$$

The radiative heat transfer co-efficient between water and glass is given by the equation,

$$h_{r,w\text{-}g} = \varepsilon_{eq} \sigma [(T_w + 273)^2 + (T_g + 273)^2](T_w + T_g + 546) \quad (13)$$

Where,

$$\varepsilon_{eq} = (1/\varepsilon_w + 1/\varepsilon_g - 1) - 1 \quad (14)$$

The evaporative heat transfer between water and glass is given by the equation,

$$Q_{e,w\text{-}g} = h_{e,w\text{-}g} A_w (T_w - T_g) \quad (15)$$

The evaporative heat transfer co-efficient between water and glass is given by the equation,

$$H_{e,\ w\text{-}g} = (16.273 \times 10^{-3}) h_{c,w\text{-}g} (p_w - p_g)/(T_w - T_g) \quad (16)$$

The radiative heat transfer between glass and sky is given by the equation,

$$Q_{r,g\text{-}sky} = h_{r,g\text{-}sky} A_g (T_g - T_{sky}) \quad (17)$$

The radiative heat transfer co-efficient between glass and sky is given by the equation,

$$H_{r,g\text{-}sky} = \varepsilon\sigma[(T_g + 273)^4 - (T_{sky} + 273)^4]/(T_g - T_{sky}) \quad (18)$$

The effective sky temperature is taken from the equation,

$$T_{sky} = T_a - 6 \quad (19)$$

The convective heat transfer between glass and sky, Qc,g-sky is given by the equation,

$$Q_{c,g\text{-}sky} = h_{c,g\text{-}sky} A_g (T_g - T_{sky}) \quad (20)$$

Where hc,g-sky is taken from the equation,

$$H_{c,g\text{-}sky} = 2.8 + 3.0\,V \quad (21)$$

The daily efficiency n_d was obtained by summing up the hourly condensate production m, multiplied by latent heat of evaporation hfg and dividing by average solar radiation Ig over the whole area. The mathematical expression is given as,

$$\eta_d = \frac{\sum m h_{fg}}{\sum A I_g} \quad (22)$$

4.2 Conventional Solar Still governing equations

Energy equation

$$E_{in} - \mathrm{E}_{\mathrm{out}} = E_{sys}$$

Conduction equation

$$Q_{COND} = [KA(T_2 - T_1)]/\Delta x$$

Convection equation

$$Q_{CONV} = hA_s(T_s - T_\infty)$$

Radiation equation

$$Q_{RAD} = \zeta\sigma A_s(T_S^4 - T_{SURR}^4)$$

Considering the thermal capacitance of saline water, the energy balance is given as,

$$\alpha_w \tau G = q_{ga} + q_b + m\, c_P \frac{dT_w}{dt}$$

Where energy losses from the water body to the glass cover and from the water body to the base of the still can be written, respectively, as,

$$q_{ga} = q_r + q_c + q_e$$

$$q_b = U_b\,(T_w - T_b)$$

Heat flux from the water to the cover by radiation qr. can be estimated using the equation,

$$q_r = F_s \sigma (T_w^4 - T_s^4)$$

In this expression, Fs is the radiation shape factor. The shape factor can be closely approximated by the emissivity of the water surface, usually taken as 0.9 for the conditions inside the still. Thus the above equation is expressed as,

$$q_r = 0.9\sigma(T_w^4 - T_s^4)$$

The heat flux from the water to the cover by natural convection and evaporation can be written, respectively, as,

$$q_c = h_c(T_w - T_g) = h_c\Delta T$$

$$q_e = m_d h_{fg}$$

The heat loss from the transparent cover to the surroundings is given by the equation,

$$q_{ga} = \varepsilon_g\sigma[T_g^4 - (T_a - 11)^4] + h_{ga}(T_g - T_a)$$

These eight equations were the key equations we used in our numerical simulations for conventional solar still analysis.

CHAPTER 5

RESULTS

Experimental analysis was performed along with numerical analysis. The results for both types were computed, plotted and compared. Physical, chemical and micro-biological tests were conducted on the output water from experimental analysis and the results were compared with raw, mineral and boiled water.

5.1 Numerical Analysis Results

Cumulative productivity of clean output water in L/m^2 was calculated for a 2cm water depth over a period of 10 hours from 9:00 am to 7:00 pm. The resulting graph is as shown below,

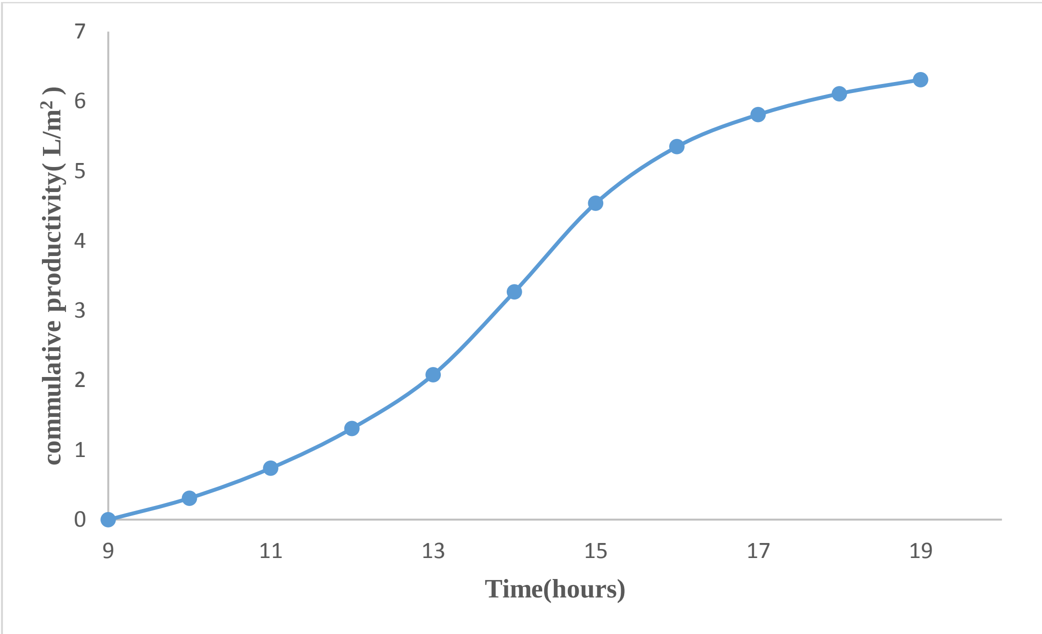

Figure 12. **Cumulative productivity in L/m^2 for 2cm water depth**

The output productivity rate was maximum between 13 to 15 hours and the total productivity obtained from numerical analysis was $6.31L/m^2$.

The effect of the water-glass temperature difference on the Productivity (Evaporation rate) of output water over a period of 8 hours from 9:00am to 5:00pm was determined through numerical analysis and the results were plotted as shown below,

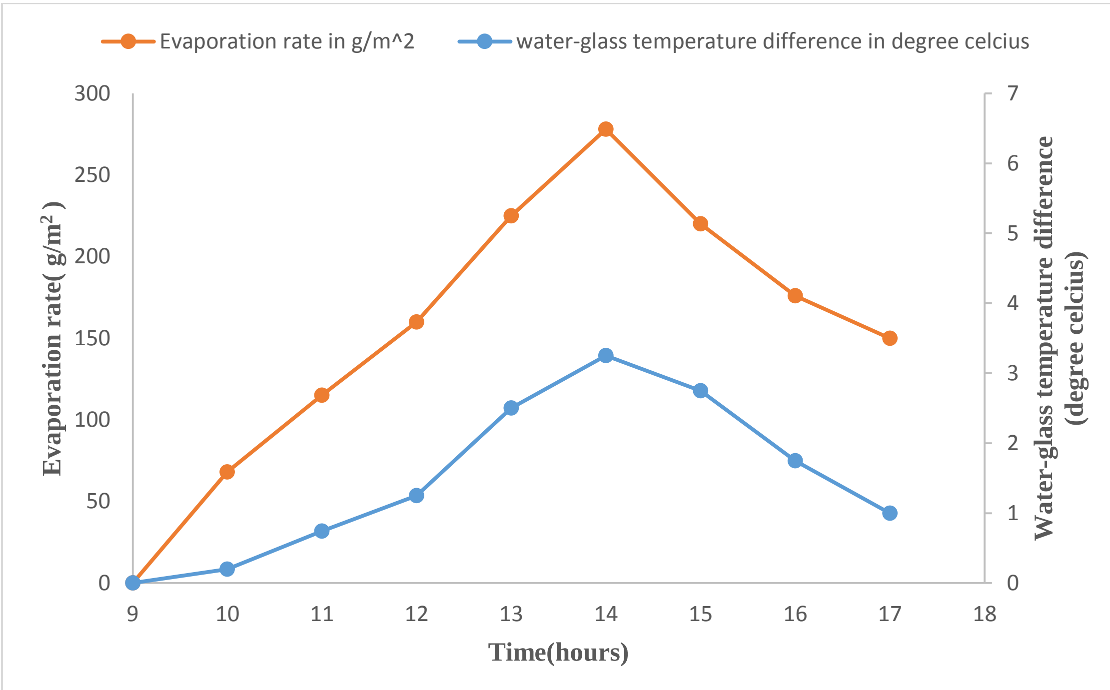

Figure 13. **Effect of water-glass temperature difference on productivity**

The evaporation rate (productivity) in g/m^2 was plotted on the left-hand y-axis while the water-glass temperature in degree Celsius was plotted on the right-hand y-axis along with time in hours on the x-axis. It was found out that the two aspects namely evaporation rate and temperature difference are in direction relation. As the water- glass temperature difference increases, the productivity increases as well. The maximum productivity obtained was 280g/m^2 for a temperature difference of 3.2 degree Celsius at 1400 hours.

The effect of variation in water depth on the productivity of clean water obtained was also determined through numerical calculations. Analysis was performed for 4 different water depths including 2cm, 3cm, 4cm and 5cm over a time period of 8 hours from 9:00am to 5:00pm and the results obtained were plotted as shown below,

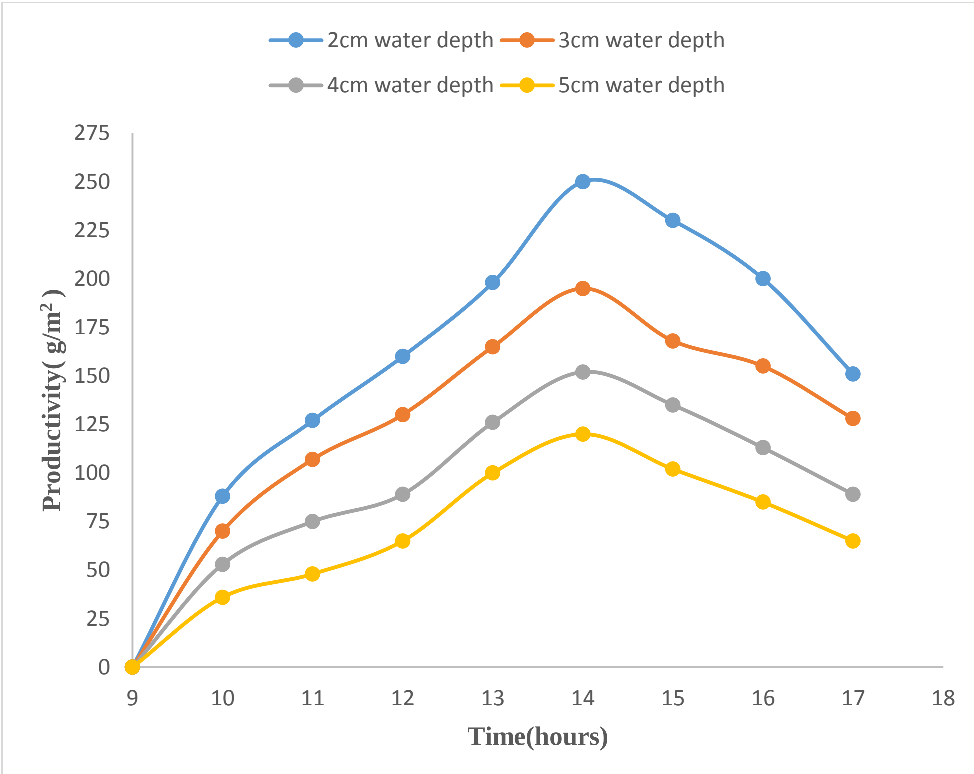

Figure 14. **Variation in productivity with water depth from 9-17 hours**

The productivity at each hour of the day increased as water depth was reduced. The highest productivity obtained was for a water depth of 2cm. The productivity for each water depth was maximum at 1400 hours.

The effect of different modifications on the daily efficiency was calculated and represented in a bar-chart format as shown below,

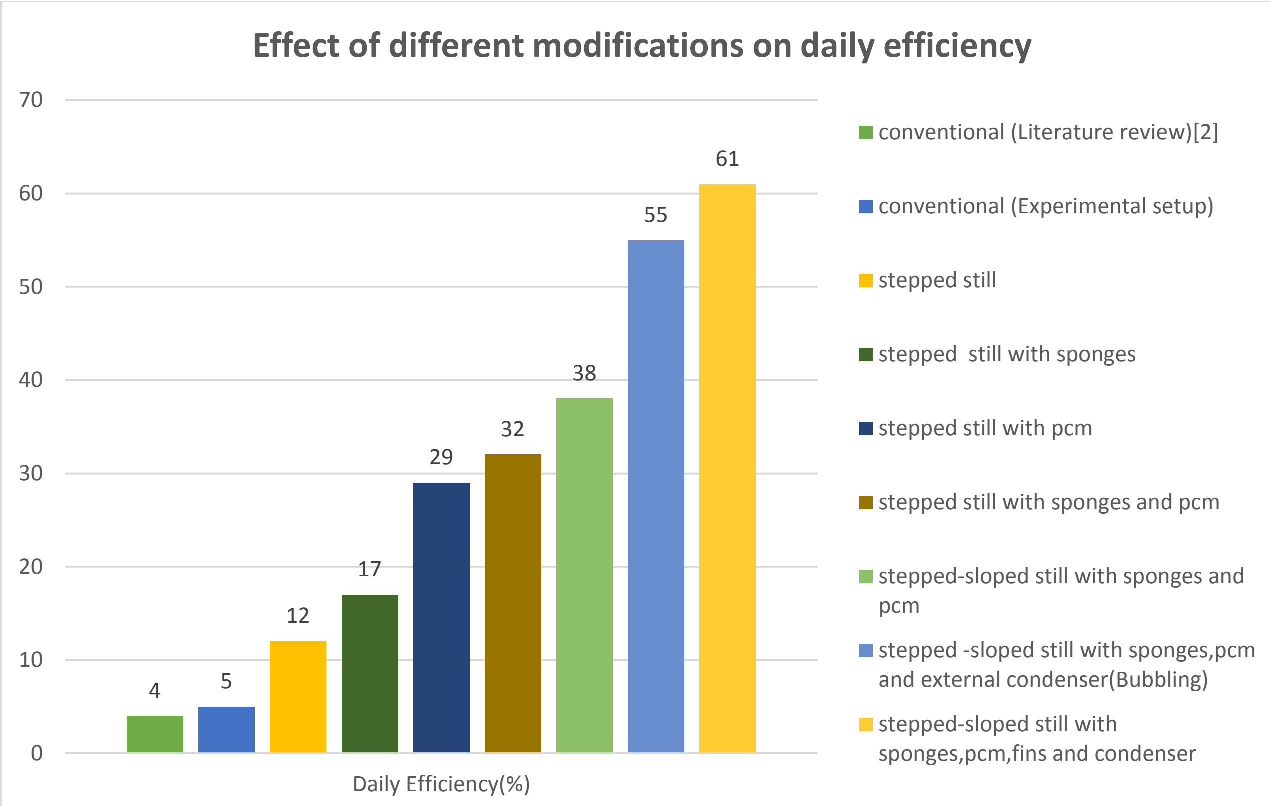

Figure 15. **Effect of different modifications on daily efficiency**

It can be seen that the daily efficiency increased with each modification. For a conventional solar still setup, the daily efficiency is 5% and in the case of our fully modified model, the daily efficiency is 61%. The biggest jump in the daily efficiency is caused by the incorporation of hot air bubbling mechanism.

5.2 Experimental Analysis Results

Experimental analysis was performed on the final prototype over a time period of 10 hours from 9:00am to 7:00pm. The hourly productivity of clean output water was noted and the results were plotted in a bar-chart as shown below,

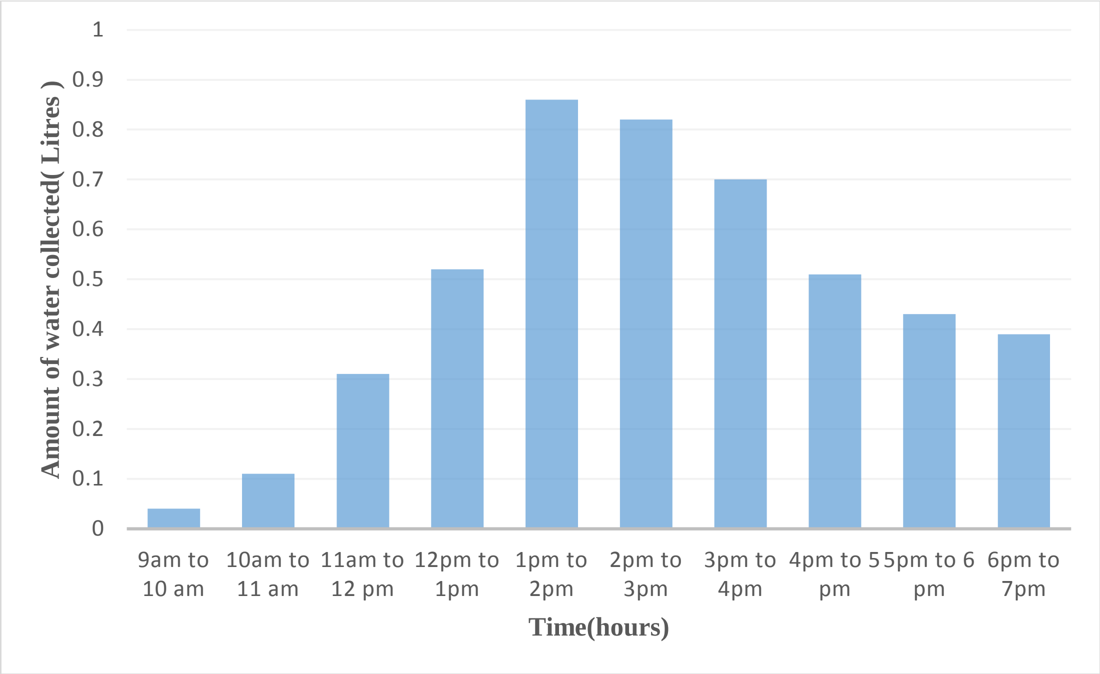

Figure 16. Experimental productivity analysis

The maximum hourly productivity was obtained between 1:00pm and 2:00pm as 0.86 Liters.

The cumulative productivity was determined and plotted as shown below,

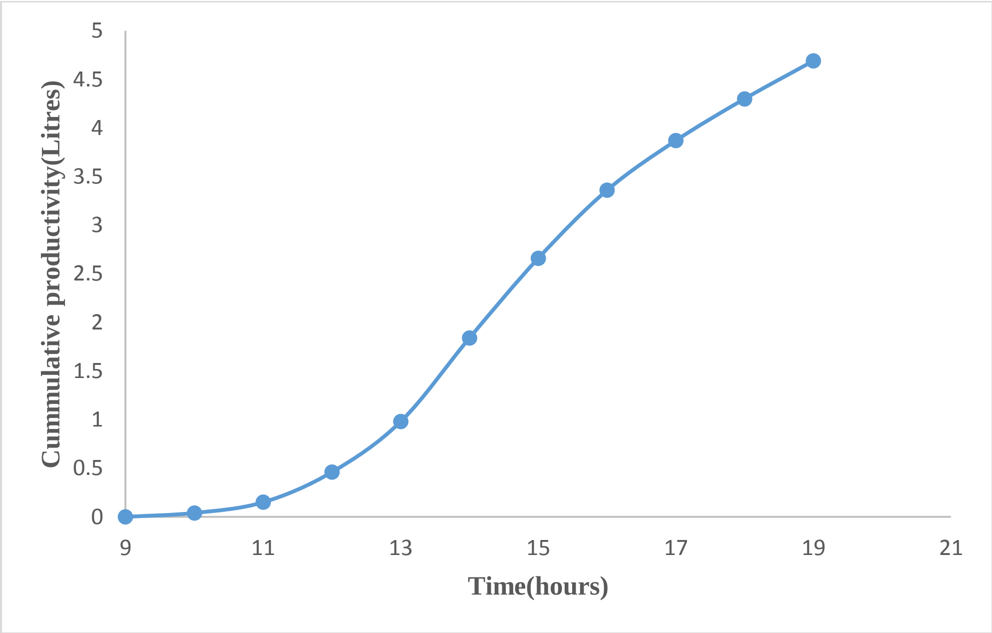

Figure 17. **Experimental productivity analysis**

The output productivity rate was maximum between 1300 to 1500 hours and the total productivity obtained from was 4.69 Liters.

5.3 Numerical Vs Experimental (comparison)

The graph below shows a comparison between the cumulative productivity determined from numerical analysis and that obtained from the experimental analysis.

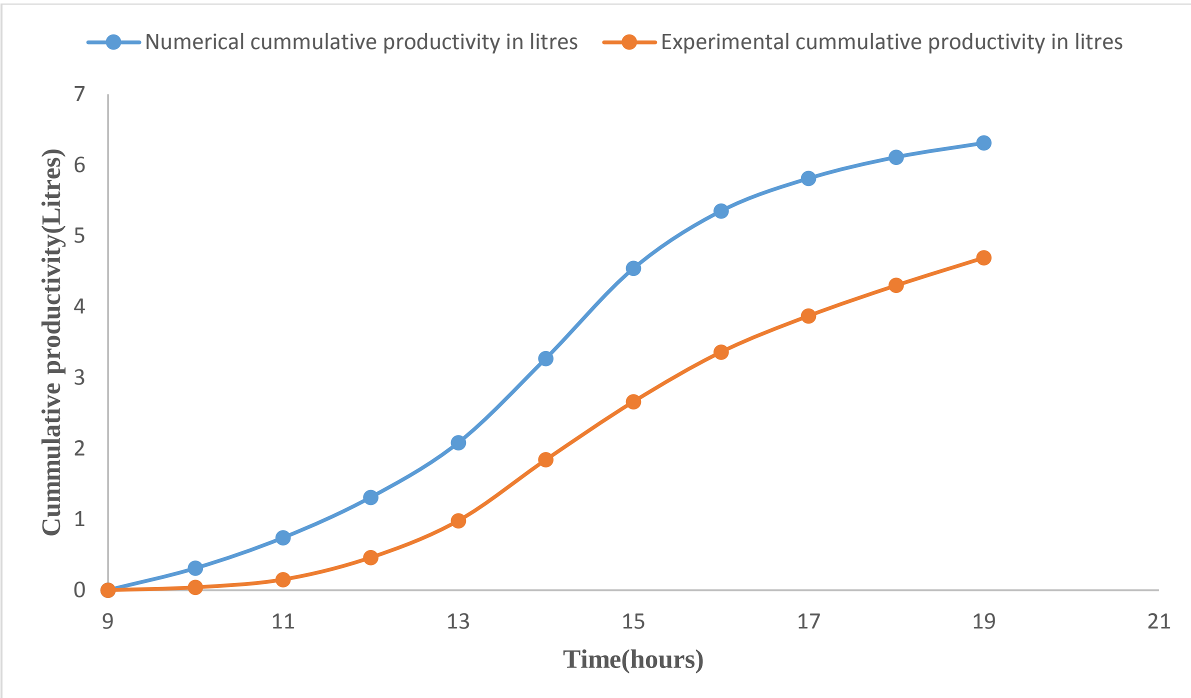

Figure 18. **Experimental Vs Numerical Productivity analysis**

The productivity obtained from experimental analysis is lower as compared to that obtained from numerical analysis due to heat losses and inefficiencies.

5.4 Physical, Chemical and Micro-Biological test results

The physical and chemical test results obtained are as shown in the table below,

Table 1. Physical and chemical test results of output water

S.NO	Parameters	Units	Raw	Mineral	Boiled	Output	WHO Guidelines	Pak Drinking Water Quality Standards
1	TDS	Mg/L	17400	360	280	187	<500	<1000
2	Turbidity	NTU	6.5	0.34	1.11	0.6	<5	<5

The total dissolved salts (TDS) in the output water and raw water are 187Mg/L and 17400Mg/L respectively, which indicates a removal of 98% total dissolved salts from raw (impure) water, hence confirming that the experimental prototype is highly effective. The TDS in output water are well within the limits setup by WHO and Pakistan drinking water quality standards.

The micro-biological test results are as shown below,

Table 2. Micro-biological test results of output water

Sample ID	Total Coliform	Fecal Coliform	95% Probability Range	WHO Limits	USEPA LIMITS	PSQCA
	MPN Index/100mL	MPN Index/100mL				
1	<1.1	<1.1	0 – 3.0	0/100 mL	0/100 mL	0/100 mL
2	<1.1	<1.1	0 – 3.0	0/100 mL	0/100 mL	0/100 mL
3	<1.1	<1.1	0 – 3.0	0/100 mL	0/100 mL	0/100 mL
4	<1.1	<1.1	0 – 3.0	0/100 mL	0/100 mL	0/100 mL

These results are negative as well, indicating that everything is between optimal limits and the output water is safe for drinking.

CHAPTER 6

POWER, AIRFLOW AND COST ANALYSIS

Our Solar still setup is not entirely passive, it does require some electrical power during its operation. Complete power, airflow (associated with the blower) and cost analysis is presented in detail in this chapter.

6.1 Power Consumption

DATA

Electric Power consuming devices in the Setup:

- 2 x fans
- 1 x blower
- 1 x motor

Power rating of fan 1(at the duct inlet) = **3W**.

Power rating of fan 2(Inside the duct behind fan 1) = **3W**.

Combined power rating of the two fans = **6W**.

Power rating of the blower = **300W**.

Power rating of the motor = **8W**.

Combined power rating of all the devices = 6+300+8= **314W**.

6.1.1 Power Analysis using Numerical values

No. of operative hours of the still/day = **10 hours (9:00am to 7:00pm).**

Water obtained via the storage tank/day = 1L 910mL = **1.91L**.

Water obtained via the main still/day = 1L 355mL = **1.355L**.

Water obtained via the external condenser/day = 3L 45ml = **3.045L.**

Total water collected from the entire setup/day = 1.38+1.02+2.29 = **6.31 L**.

$$E = Px\ t$$

$$E = \frac{314}{1000} x\ 10 = \mathbf{3.14}\boldsymbol{KWh}$$

Energy consumption per liter of water collected per day = $\frac{3.14}{6.31}$ = **0.4976KWh/L (each day).**

6.1.2 Power Analysis using Experimental values

No. of operative hours of the still/day = **10 hours (9:00am to 7:00pm).**

Water obtained via the storage tank/day = 1L 380mL = **1.38L**.

Water obtained via the main still/day = 1L 20mL = **1.02L**.

Water obtained via the external condenser/day= 2L 290ml = **2.29L.**

Total water collected from the entire setup/day = 1.38+1.02+2.29 = **4.69 L**.

$$E = Px\ t$$

$$E = \frac{314}{1000} x\ 10 = \mathbf{3.14}\boldsymbol{KWh}$$

Energy consumption per liter of water collected per day = $\frac{3.14}{4.69}$ = **0.669 KWh/L (each day).**

6.2 Airflow into the Still via the Blower

Diameter of the blower = 7.2cm = **0.072m**.

Diameter of the inlet pipe = 2.1cm = **0.021m**.

Operating rpm of the blower = N = **9500rpm**.

Density of air at rtp = **1.23kg/m^3**.

Angular velocity = w = $\frac{2n\pi}{60} = \frac{2 \ x \ 9500 \ x \ \pi}{60}$ = **994.84rad/s**.

Velocity of air into the inlet pipe = v = angular velocity x radius of the blower = 994.84 x (0.072/2) = **35.81m/s.**

Cross-sectional area of the inlet pipe = π x (d^2/4) = π x (0.021^2/4) = **3.46x10^{-4}m^2.**

Mass flow rate of air into the inlet pipe = density x cross-sectional area x velocity = 1.23 x 3.46x10^{-4} x 35.81 = **0.0152kg/s.**

6.3 Cost Analysis

(a) Cost of system (material and fabrication) = Rs (30050 + 9850) = Rs 39900 approximately Rs 40000

Design life of the system = **10 years.**

Approximate number of days the system operates in one year = **300.**

Production of water per day = **4.69L.**

Total production of water in 10 years = 10 x 300 x 4.69 = **14070 L.**

Cost of water/L = 40000/14070 = **Rs 2.84.**

(b) Energy consumed each day = **3.14 KWh.**

Energy consumed/L = **0.669 KWh.**

Energy consumed in one month = 3.14 x 30 = **94.2 KWh.**

Tariff of electricity for less than 100 unit per month is **Rs 5.79.**

Cost of water/L = 0.669 x 5.79 = **Rs 3.87.**

(c) Total cost of water produced/L = Rs(2.84 + 3.87) = **Rs 6.7.**

Cost we face in one day for producing 4.69L of water = 4.69 x 6.7 = **Rs 31.42.**

(d) Pay back analysis

Average selling cost = **Rs 35/L.**

Selling cost per day = 4.69 x 35 = **Rs 164.15.**

Payback period = investment/net earnings per day.

Net earnings per day = 164.15 – 31.42 = **Rs 132.73.**

Payback period = 40000/132.73 = **301.36 days**.

Which is less than 1 year approximately **10 months!**

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

A few important conclusions which we have drawn from our project and some future work which needs to be done on the project are discussed in this chapter.

7.1 Conclusions

The following conclusions are drawn from our final year project:

- Minimum water depth (2cm) maximizes the productivity.
- The larger the water-glass temperature difference the larger the evaporation rate/productivity.
- The productivity calculated by numerical analysis is 6.31 L/day.
- The productivity obtained experimentally is 4.69 L/day which is slightly lower than the numerical value owing to heat losses.
- Modifications such as stepped-sloped configuration, sponges, fins, PCM, bubbling with external condenser enhance the daily efficiency and productivity by 61%.
- The biggest jumps in daily efficiency are due to paraffin wax (PCM) which increases daily efficiency by 12% and hot air bubbling mechanism which increases the daily efficiency by 17%.
- The total dissolved solids (TDS) and Turbidity in the output water are greatly reduced which shows good removal efficiency of the setup.
- Microbial analysis reveals that the output water sample is free from coliform and fecal coliform hence safe for drinking.

7.2 Recommendations

Some future work and suggestions for our project are:

- Proper solar tracking of the multistage stills as well as external reflectors still needs to be done.
- The stills must be incorporated with Fresnel lens and a parabolic trough because these two modifications enhance the productivity to a great extent.
- A complete computational fluid dynamics (CFD) analysis needs to be performed.

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APPENDIX 1. PROPERTIES OF PARAFFIN WAX

Melting Point	Between 46 and 68 degree Celsius
Density	900 kg/m^3
Solubility In Water	Insoluble
Heat Of Combustion	42 KJ/kg
Resistivity	Between 10^{13} and 10^{17} Ohm meter
Specific Heat Capacity	2.14-2.9 J/gK
Heat Of Fusion	200-220 J/g
Thermal Conductivity (at 25 ℃)	0.25 W/mK
Boiling Point	Greater than 370℃ (698°F)
Appearance	White and Light Yellow Color
Chemical Formula	$C_{31}H_{64}$ (Hydrocarbon) is the main component of paraffin wax.
Odor and Taste	Odorless , Tasteless and Waxy Solid
Molar Mass	507 g/mol
Refractive Index	1.442-1.448

APPENDIX 2. MATERIALS USED IN MANUFACTURING

MATERIALS	USES
Acrylic Sheets (6mm and 4mm)	Base and Walls of Storage Tank and Main Still
Transparent Glass (3mm)	Top Cover of Storage Tank and Main Still
Aluminum Sheets	Stepped-Sloped Trays
Polyvinyl Chloride (PVC)	Pipes , Ducts and PVC fittings
Sponges	Increasing Surface Area for Evaporation
Stainless Steel 430 (0.4mm thick)	Reflectors
Wood	Reflector Stands
Packing Material , Saw Dust and Glass Wool	Insulation
Paraffin Wax (White and Light Yellow)	Phase Change Material (PCM)
Copper	Condenser Coil
Stainless Steel	Condenser Box
Stainless Steel 304	Connecting Pipe
Black Paint	On Trays to Enhance Heat Absorption
Carbon Steel	Supporting Stands for Main Still and Storage Tank
Silicone Gel	Sealant
Chloroform	Joining Acrylic Sheets

APPENDIX 3. TOOLS USED IN MANUFACTURING

TOOLS	USES
Drill Machine (Bits and Cutters)	For Drilling Holes
Grinder and Cutting Disks	For Cutting Acrylic,Aluminum and Stainless Steel Sheets
Rivet Gun	Riveting
PVC heater	Joining PVC fittings/Pipes
Hot Melt Glue Gun	Joining Materials
Bending Machine	Bending Aluminum Sheets
Hammers (Claw , Ball peen and Sledge)	Hammering
Hand Saw	Cutting Wood
Different Scissors/Snips/Chisels	Cutting Different Materials and Aluminum
Special Cutters	For cutting Acrylic Sheets
Silicone Gun	For Holding Silicone Gel Bottle and Application of Silicone Gel
Phillips and Slotted Screwdrivers	For Fixing Fasteners
Nose Plier and Adjustable Ranch	For Fixing Fasteners
Level and Bevel Gauges	Levelling and Angle Measurement
Chalk Line and Measuring Tape	For Taking Measurements
Spring	To Coil The Copper Pipe
Welding Plant	For Construction of Supporting Stands and Fixing Tires to the Solar Stills

APPENDIX 4. INSTRUMENTATION

INTRUMENTATION	USES
Blower	For Bubbling in Last Tray
2 Exhaust Fans	To Suck Vapors in to the Condenser
Motor/Pump	To Pump Water From the Main Still in to the Storage Tank
Thermocouples	Temperature Measurement
Hygrometer	Humidity Measurement
Graduated Flasks	Output/Pure water Collection and and its Volume Measurement
Laser Thermometer	Temperature Measurement and Monitoring

THE END