THERMAL ANALYSIS OF A SINGLE SLOPE PASSIVE SOLAR STILL

A THESIS SUBMITTED IN FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF

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VIRENDER SOLANKI

REGISTRATION NO: 801783016

UNDER THE SUPERVISION OF

DR. SAYAN SADHU

ASSISTANT PROFESSOR

MECHANICAL ENGINEERING DEPARTMENT

THAPAR INSTITUTE OF ENGINEERING AND TECHNOLOGY,
(DEEMED TO BE UNIVERSITY)
PATIALA-147004, PUNJAB, INDIA

AUGUST, 2019

CERTIFICATE

I hereby declare that the dissertation entitled "**Thermal analysis of a single slope passive solar still**"a "Theoretical Investigations" is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering in Thermal Engineering** at **Thapar Institute of Engineering and Technology, (A Deemed to be University), Patiala** under the supervision of **Dr. Sayan Sadhu** (Assistant Professor, Mechanical Engineering Department). No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

Virender Solanki

Virender Solanki
801783016

Date: 21th-August-2019

It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

Sayan Sadhu

Dr. Sayan Sadhu
Assistant Professor
Mechanical Engineering Department
Thapar Institute of Engineering and Technology,
(A Deemed to be University), Patiala-147004, Punjab.

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Virender Solanki
801783016
Mechanical Engineering Department
Thapar Institute of Engineering and Technology

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Nomenclature

A_b	Basin area of still (m^2)
A_w	Water surface area of still (m^2)
A_g	Glass cover area (m^2)
C_w	Specific heat of water in solar still (J/kg°C)
h_b	Heat transfer coefficient from basin liner to ambient air via bottom insulation (W/m^2°C)
h_{1g}	Convective heat transfer coefficient from glass cover to ambient (W/ m^2 °C)
h_{1w}	Heat transfer coefficient from water surface to glass cover (W/ m^2 °C)
h_w	Convective heat transfer coefficient from basin liner to water (W/ m^2 °C)
h_{cw}	Convective heat transfer coefficient from water surface to glass (W/ m^2 °C)
h_{ew}	Evaporative heat transfer coefficient from water surface to glass (W/ m^2 °C)
h_{fg}	Vaporization heat, (J/kg)
I(t)	Solar intensity on the glass cover of the solar still (W/m^2)
LH	Latent heat of vaporization (J/kg)
M_w	Mass of water in basin (kg)
M_{ew}	Hourly output of still (kg/ m^2 h)
T_a	Ambient air temperature (°C)
T_b	Basin temperature (°C)
T_{ci}	Inner temperature of condensing cover (°C)
T_w	Average water temperature (°C)
T_g	Average glass temperature (°C)
UL	Overall heat transfer coefficient (W/m^2 °C)

Q_{loss}	Heat loss from basin to ambient, (W/m^2)
V	Wind speed (m/s)
J(i)	Solar intensity per sec

Greek letters

α	Absorptivity
τ	Transmittivity
β	Glass cover angle (°)
ε	Emmisivity
σ	Stefen Boltzman constant, (W/m^2K^4)
ρ	Density (kg/m^3)

Subscripts

b	Basin liner
g	Glass cover
w	Water
m	Melting
l	Liquid
r	Radiaton
equ	Equivalent
a	Ambient
c	Convection
ev	Evaporation

1w	Overall heat transfer coefficient from water to glass heat transfer
1g	Overall heat transfer coefficient from glass cover to ambient
B	Bottom
sky	Sky
S_w	Saline water
abp	Absorber plate

Superscript

n	Geometric constant in Nusselt number relation
C	Coefficient of Nusselt-Rayleigh Number relation

Dimensionless Numbers

Gr	Grashofs Number
Pr	Prandtl Number
Ra	Rayleigh Number
Nu	Nusselt Number

ABSTRACT

Water is an essential element for a living organism on earth. 71% of the earth's surface is covered with water and seawater hold approximate 97% of earth's water that is highly salty. The ratio of freshwater to salty water on earth is 1 to 40. Freshwater on earth is available in the form of rivers, lakes, in glaciers and it can be used directly. However, population growth and industrialization have resulted in high demand for freshwater for domestic, agriculture and industrial use. Also, water distribution is uneven on the earth surface. So freshwater shortage is a major problem in underdeveloped and developing nations. so desalination of the seawater is the only option left.

The use of solar energy for desalination are popular choices nowadays.

In the present study thermal analysis of passive single slope solar still and a still with the use of PCM (paraffin wax) via mathematical modeling is done to predict the behavior of still. Their performances are compared on the basis of the mass of distillate produced by them. It was observed from theoretical investigations that still consisting a PCM is efficient than the conventional one by up to 83%. Also, the thickness of PCM has no significant effect on productivity. With an increase in water depth from 2cm-15cm, there was loss in productivity up to 30%. Loss in productivity is due to sensible heat of water, hence lower operational values are suggested of range 2-5cm for optimum efficiency. Wind speed on glass cover has no significant effect on the productivity of still with a maximum variation of 9% for a speed range of 1-5 m/sec. Also, the slope angle is an important design parameter. The present study shows that optimum slope angle changes with the season. Optimum slope cover angle can be different for summers and winters. Slope angle should be designed according to summers as water requirement is high in summers as compared to winter

KEYWORDS: Solar still, Desalination, Heat transfer, Phase change materials, Mathematical modeling.

CHAPTER 1
INTRODUCTION

Freshwater is a basic need for human on earth. But it is very much limited in nature as almost 97% of the total water is in the ocean which is salty and hence we are not able to use it directly. This salty water is neither drinkable nor usable for daily works. It is estimated that by the present rate of consumption of water there would be a scarcity of water in 2030 for 30% people around the world. There are many countries who are facing huge scarcity of water nowadays especially in the middle east and African countries. In a report, the World Health Organization (WHO) mentioned that human need is 60-100 litres to ensure the basic need is not available in these countries [42]. In India, this problem would be getting serious in the coming 10 years and already some parts of the country facing this issue. Waterborne diseases are very common in areas where the availability of freshwater is not in adequate quantity.

Billions of instances of diarrhea have been recorded annually and around 90% of them because of the lack of fresh/clean water intake [7]. These problems indicate that there is a growing necessity to work on the desalination process to convert the salty water to a fresh one which can be useful. Increase in pollution is also a growing problem in the environment, the effect of greenhouse gases can be seen on the atmosphere as the average temperature has been increased. In general, the use of fossil fuels is considerably subsidizing to climate alteration as a waste product of hydrocarbons are CO, CO_2 and other harmful gases leading to the higher carbon footprint.

Consequently, the use of renewable energy in the production of useful water can help to decrease pollution levels and to restore balance in the ecological system.

Various methods are available to produce potable water and they are cost-effective too but the problem is the quantity of energy we are giving to get a unit output of water is higher and there is a need for the periodic maintenance of equipment used., The only solution to meet this growing useful water demand is via distillation. The solar stills that use solar power are one of the favorable method. for obtaining the useful water for even small scale demand as it is their simple to use eco-friendly in nature, easy to install and at the same time they are cost-effective too.

1.1 NEED FOR SOLAR DISTILLATION

The distribution of water on earth's surface is very much uneven, only, 3% of water is in the form of useful water. Of this useful water, 69% is in the glaciers i.e in the north pole and south poles, 30% of water is underground water and less than 1% is in rivers and lakes, etc. Remaining 97% water is in the form of oceans and is it's salty and thus cannot be used directly for drinking or household purpose, agriculture and industrial use etc. [42]

Heat required to vaporize water is known as latent heat of vaporization of water, and its value is 2260 kJ/kg for 1 atm pressure. That means to yield 1 Litre (i.e. 1 kilogram, as the density of water is 1 kg/litre) water i.e. freshwater, the heat required is 2260 kJ. Usually, more heat requires to produce 1k.g of water as the efficiency of a heating source is not 100%.

1.2 PRINCIPLES OF A SOLAR DISTILLATION SYSTEM

It is simple in construction and easy to fabricate. Its made of galvanized iron and is made insulated from all sides by using insulation materials. Basin's internal surface known as basin liner is painted black so that it competently absorb the solar insolation incident on it. A special kind of arrangement is made for the collection of the output pure water on the sides of the still or on the lower ends of the still. The brine or brackish water is provided in the basin for the purification process. The basic principle of the desalination process resembles raining process in nature.

In Solar distillation is a process which solar energy is used as thermal energy directly for obtaining useful water from the brackish water. The equipment is known as a solar still, it consists of a basin which is blackened from inside so as to absorb the maximum amount of incident rays and the still is covered with a transparent glass cover. The brine water is filled in the basin and the sun's rays that are incident on glass cover heats the basin which acts as a heat source for water and water vapor forms at glass cover as shown in figure (1.1). Energy absorbed in bottom liner largely transferred to the water by conduction and convection mechanism. A small amount of energy loss via the bottom of still by conduction mechanism. At the water surface, the energy transferred to glass cover by convection, evaporation, and radiation. By diffusion and convection, the vapor is transferred to cover. These vapors then get condensed on glass cover by losing latent heat of condensation and then collected on side corners by collector trough. Hence salt and other minerals present in the water left behind in basin only as shown in figure (1.2).

Incoming radiation is one of the important input variables in solar distillation which is transient in nature throughout the day. Sun rays i.e. solar radiation can be estimated from the position of the sun at any particular time of the day(hour angle), the latitude of the location, solar altitude, and azimuth angles, surface tilt angle, etc. All these parameters affect the quantity of solar insolation on a given surface.

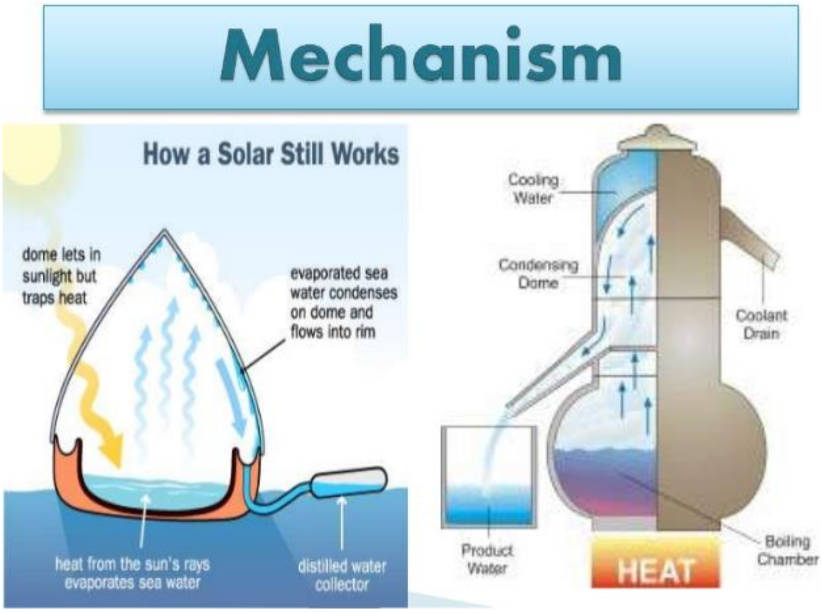

Figure 1.1: Working of a solar still [1]

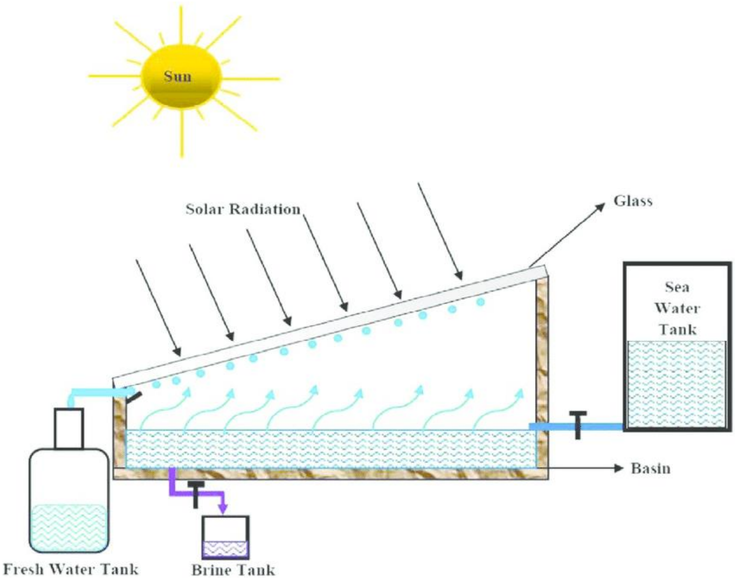

Figure 1.2: Schematic diagram of simple single slope still [2]

1.3 CLASSIFICATION OF SOLAR STILL SYSTEMS

Different types of solar stills, including basin and wick type still, have been produced as known in the literature as shown in figure (1.3). In a basin type solar still, water in the basin is heated with black colored basin liner. The water surface is then heated and vapor starts to form, these vapors are then collected in collector trough. this is a simple type of process with minimum efficiency, however, there are several attempts made which suggests improvement in efficiency. A black colored wick soaks water from the basin and gets heat energy from incoming solar radiation, water evaporates and condenses on the glass cover which is below the saturation temperature corresponding to the partial pressure of water vapor present, the condensate is then collected by the same method as above. This method has improved efficiency. Basin type solar stills are common and more user-friendly as easy to install and maintain.

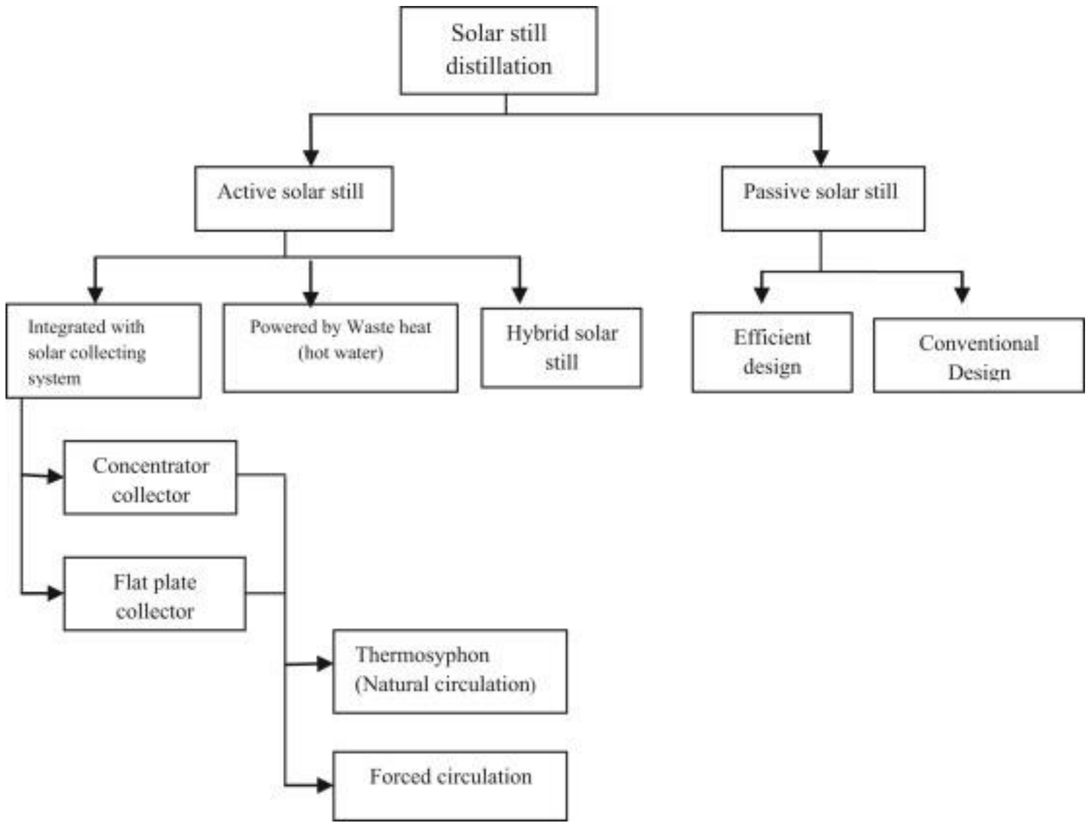

Figure 1.3: Classification of solar stills [3]

1.3.1 PASSIVE SOLAR STILLS:

Passive solar stills consisting of a glass cover to trap solar energy and water basin to store brine. It is simple in construction as shown in figure (1.4) and cost-effective. As there is no external attachment to it like pump, solar collector e.t.c so it's maintenance-free too. There are various methods can be implied to improve the productivity of still like condenser part on glass cover, nanofluids on water, the external heat source in non-sunshine hours. These are very popular in rural areas and suitable for domestic use, large scale use like industrial use is also possible by modifying still. Some example of conventional type passive type stills are :

1. Single slope solar still (figure 1.5)
2. Modified single slope solar still
3. Double slope still
4. Stepped solar still
5. Tubular solar still
6. Vertical still and inclined solar still

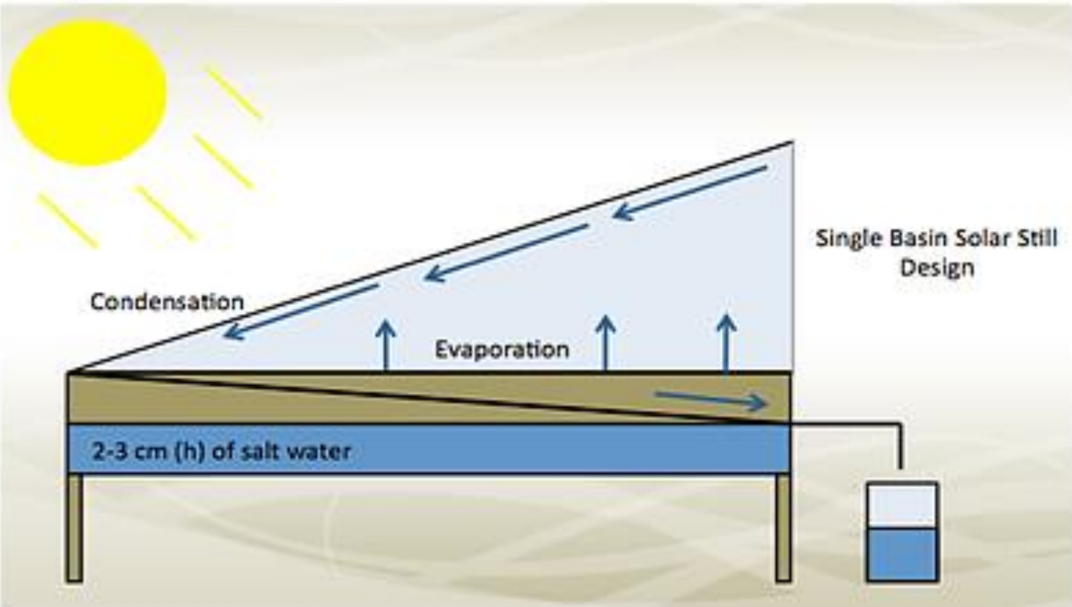

Figure 1.4 Passive type single slope still [4]

Figure 1.5: Real-time view of single slope passive type still [4]

1.3.2 ACTIVE SOLAR STILL

The output of a still depends on water temperature and glass temperature. The water temperature in still depends on solar insolation on the still surface. Productivity also depends on water depth. The surface temperature of water can be increased by increasing feed water temperature, this type of still is called active type still. Active type stills use external heating along with regular heating as shown in figure (1.6). So more moving or added parts makes it costly. So the initial cost is high and maintenance cost also increases.

Advantage of such kind of systems is that they provide high productivity and provide output in even non-sunshine hours. Some of the examples of active still are as follows:-

1. Solar still with a flat plate collector, parallel plate collector
2. Vertical solar still with a flat plate collector
3. Still consolidated along with a parabolic collector
4. Solar still attached to a solar pond

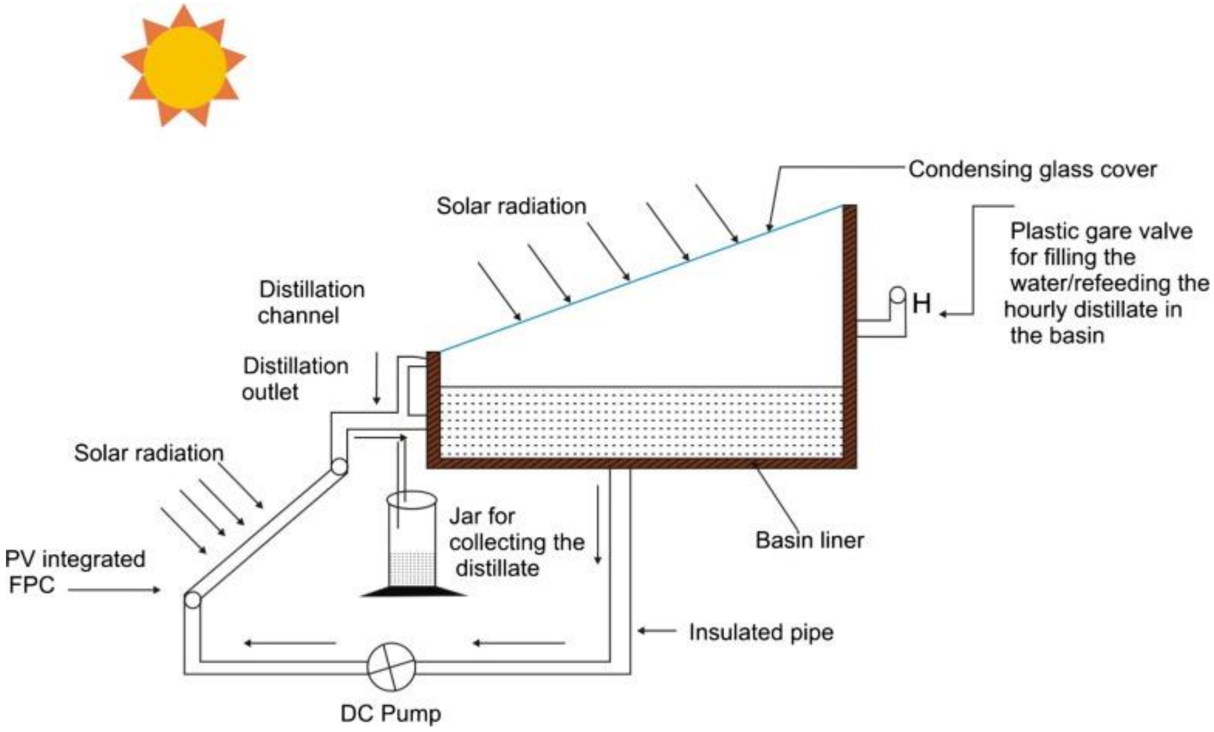

Figure 1.6: Schematic of an active type of still [5]

1.4 HEAT AND MASS TRANSFER IN A SOLAR DISTILLATION UNIT

The solar desalination process basically involves three modes of heat transfer. From the bottom and the sides of still its conduction which is responsible for heat losses. These losses can be minimized by using layers of insulating material. The heat from basin liner to water is transferred mainly through convection and from water to glass cover heat is transferred by three processes i.e convection, evaporation, radiation. Water vapor condenses on the glass cover as it losses the latent heat of vaporization from glass cover and distilled condensate water is produced. The heat from glass cover is transferred to the environment via convection and radiation. There is mass transfer involved with the internal heat transfer in still as there is condensation and evaporation occurred in the system.

1.4.1 INTERNAL HEAT TRANSFER

Heat transfer between water surface inside basin and the inner glass cover of still is under internal heat transfer study. Motion of water-vapor mixture, evaporation of liquid, condensation of vapor studied under this part. Figure (1.7) shows heat resistance circuit from the bottom of still to top glass cover of a still.

1.4.1.1 CONVECTIVE HEAT TRANSMISSION

Convection heat transfer includes heat transfer by the bulk motion of the fluid. There are broadly two types of convection, one is .free or natural convection and another is forced convection. In a solar still, the natural or free convective heat transfer takes place between basin liner to water and then from water to inner glass cover. This is because of the temperature difference between the two surfaces.

1.4.1.2 EVAPORATIVE MASS TRANSFER

Mass transfer occurs from water surface and inner glass surface inside solar still. Water converts into the vapor by gaining the latent heat of vaporization when the solar radiation falls on its surface. The water vapor then gets condensed at the relatively cold glass surface by losing the latent heat of condensation to the environment via glass cover.

1.4.1.3 RADIATION HEAT TRANSFER

This mode of heat transfer by the emission of radiation from one surface at a given temperature. Radiative heat transfer takes place between two surfaces (water and glass). Radiation transmission does not require any medium

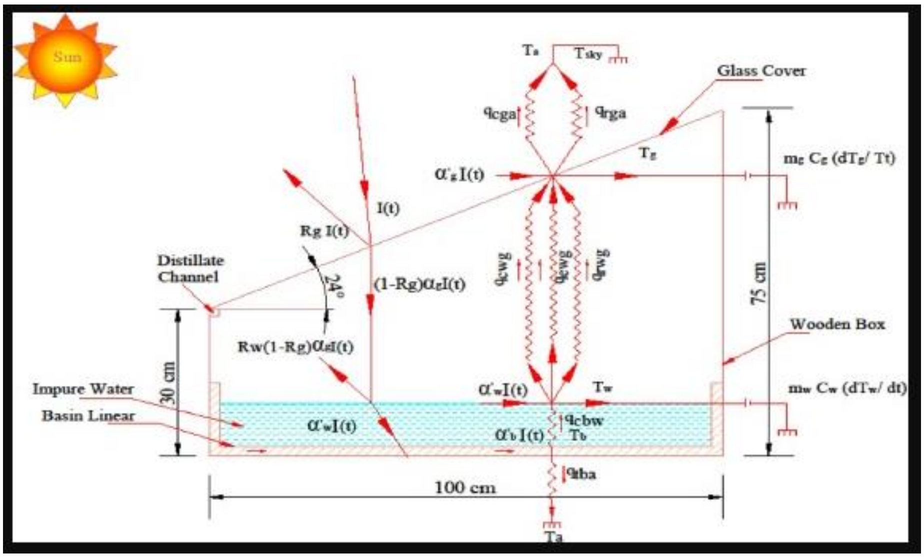

Figure 1.7: Heat transfer in solar still [6]

1.4.2 EXTERNAL HEAT TRANSMISSION

External heat transfer includes heat exchange with the environment. It can be possible with the convection and radiation phenomenon in the current topic. In the present still, the external heat transfer takes place from the solar still to the atmosphere. Such type of heat loss is a top loss, bottom loss, side loss heat transfer. Other than top loss rest is negligible. Top heat transfer is due to convection and radiation only.

1.5 PHASE CHANGE MATERIALS (PCM)

Materials which can store energy(heat energy)in both sensible heating and latent heating are known as PCM. The thermal energy storage capability of PCM is higher than the sensible heat storage medium. These materials are very suitable for heat absorption and can release energy by undergoing a phase change.

The following types of phase change take place as follows:
1. solid to gas
2. liquid to gas
3. solid to liquid

1.5.1 WORKING OF PCMS

In order to act as a thermal source, a PCM absorbs energy from surroundings and releases the thermal energy when the temperature of the surroundings falls. The process becomes isothermal when the surrounding temperature becomes equal to the melting temperature of PCM. When PCM starts to melt i.e. the phase change takes place from solid to liquid. During this process, it absorbs a large amount of latent heat without any change in the temperature. Reverse of this process occurs when the temperature of surrounding cools down. It losses all its energy to surrounding with changing in its phase from liquid to solid. So this reversible process is known as solidification

1.6.2 PCM CLASSIFICATION

These are basically of three types as shown in figure (1.8)

1. Organic PCM

2. Inorganic PCM
3. Eutectic PCM

In the present study, we only concern about the first two. Organic PCM are favorable always as they bring nothing serious to the environment.

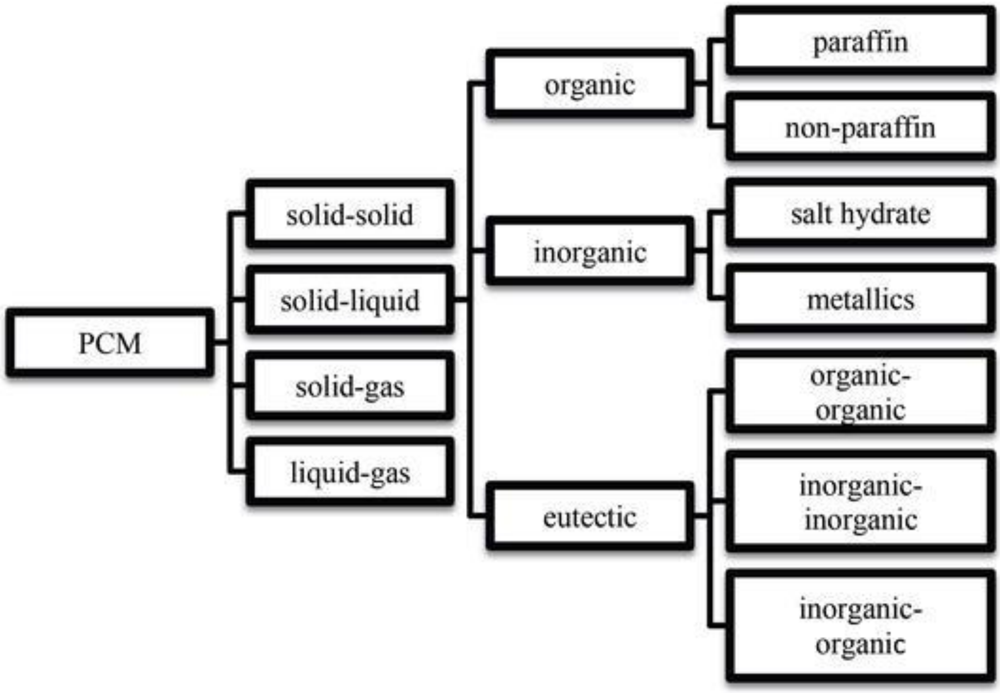

Figure 1.8: Classification of PCM [8]

1.6.2.1 ORGANIC PCMS

Organic resources are categorized as paraffin and non-paraffin compounds. These have the ability to change phase continuously without affecting efficiency.

Paraffins: Paraffins are hydrocarbons and are given as C_nH_{2n+2}. These exist in the form of wax at room temperature generally. These are widely used in various application where there is a need for thermal storage material. Figure (1.9) shows the view of paraffin wax.

Some advantages and disadvantages of paraffin are:-

Table 1.1 Advantages and disadvantages of paraffin's

Advantages	Disadvantages
They don't separate	They have low conductivity.
They are non-corrosive, safe and easy to use	Some paraffin in their pure form are expensive but low-grade paraffin are Cheaper.
They are accessible in a different temperature range and chemically stable	They are flammable.

Figure 1.9 Paraffin wax [43]

Non-paraffins: These types of organic PCMs have diverse properties. Each of this kind has unique property but paraffin posses the same kind of properties. Examples of such type of PCM are glycerine, formic acid, phenol, etc.

These materials are highly combustible and should not expose to heat (high heat), fire. Pros of using them as the high heat of fusion but at the same time, they possess low conductivity, flammability and gets unstable at high temperature.

1.5.2.2 INORGANIC PCMS

In-organic PCM are of two types -salt hydrates and metallics. These materials do not cool easily and also they don't deteriorate easily.

Salt hydrates: These are crystalline form of a combination of salt and water. Melting point range of these salt hydrates probably within 15-17 ^oC. Some important PCMs falling in this category are $Mg(NO_3)_2.6H_2O$, $Na_2SO_4.10H_2O$, $Na_2CO_3.10H_2O$.etc

Metallics: These types of PCM have heavyweights, hence not usable for where weight is constrained. They are used where the weight is not an issue. Such types of PCM have a relatively low vapor pressure. Gallium, cerrobend eutectic, etc are some examples.

1.5.2.3 Eutectics: PCM which are formed by the combination of two or more constituents are Eutectics**.** In this type of PCMs, each element melts and freezes conjointly forming a crystal. Segregation of components is not possible as at the time of melting the components liquefies at the same time. These can be sub-divided in inorganic-inorganic, organic-organic and inorganic-organic. Some examples of such types of PCM are

Triethylolethane+ H_2O +urea, $CaCl_2.6H_2O+CaBr_2.6H_2O$, $CaCl_2+MgCl_2.6\ H_2O$ etc.

1.6 PARAMETERS AFFECTING THE OUTPUT OF A SOLAR STILL

The productivity of a solar still mainly depends on three parameters

1. Operational parameters.
2. Design parameters
3. Meteorological parameters

1.6.1 EFFECT OF OPERATIONAL PARAMETERS OF SOLAR STILL

Operational parameters include the factors which affect the efficiency at the time when still starts working. Examples are- water depth, the coloring of water, the salinity of water, algae growth e.t.c.

1.6.1.1 EFFECT OF WATER DEPTH

Low water depth results in low heat capacity and high yield for same given conditions. Especially in the morning when solar insolation is low so a high amount of heat required to heat the water and to form water vapors.

1.6.1.2 EFFECT COLORING OF WATER

By mixing charcoal, and nano-fluids in basin water, absorbtivity of water increases. An increase in basin water temperature increases the temperature difference between water and glass cover. Hence increase productivity.

1.6.2 EFFECT OF DESIGN PARAMETERS OF SOLAR STILL

These parameters are considered most important while constructing a solar still for real-time problems. Example are orientation of still, glass angle, gap between water surface and glass cover e.t.c.

1.6.2.1 EFFECT OF THE GAP DISTANCE

The gap between the evaporative surface and condensing surface should keep low as to get high distillate output. Low gap makes vapor to reach the condensing surface quickly.

1.6.2.2 EFFECT OF NUMBER OF COVERS

It does make still airtight by using no of covers and helps to maintain inner glass cover at a higher temperature.

1.6.3 EFFECT OF AMBIENT CONDITIONS ON SOLAR STILL

These effects are environmental effects which are beyond scope of human design. These factors affects the efficiency of solar still. Examples are wind speed, ambient temperature, solar irradiance, outside humidity e.t.c.

1.6.3.1 EFFECT OF WIND VELOCITY

Effect of wind velocity is not certain as it may increase output for a low value of velocity than zero velocity and can decrease still output with an increasing velocity at evening time or in non-sunshine hours as convection increases at glass surface and increase heat loss and makes still cooler easily.

1.6.3.2 EFFECT OF AMBIENT AIR TEMPERATURE

The effect of ambient temperature variation on solar still productivity is considered as a slight increase in ambient temperature can increase still output.

1.6.3.3 EFFECT OF SOLAR INTENSITY

In a still, output is directly proportional to solar insolation. Many researchers gave the relation between still output with solar insolation on the surface.

1.6.4 OTHER EFFECTS

Increase in concentration of feed water in still can decrease distillate output. also scaling can decrease the efficiency of absorber surface. the concentration of water that feeds into the basin affects the performance badly, as an increase in concentration results in the huge residue of salt inside the basin bottom. It reduces the absorbtivity of the basin bottom and also at the same time cleaning of the bottom is also a challenge. Preheating of water increase the efficiency as less amount of energy required to raise water temperature inside. Other factors like algae growth and sky condition also affect the efficiency of a solar still.

1.7 THESIS ORGANISATION

CHAPTER 1: Introduction briefs about the process of desalination, it's working principal, application, classification, different modes of heat and mass transfer study of still, use of phase change materials, in conjunction with solar still, different operating and geometric parameter affecting the still performance.

CHAPTER 2: Literature review gives the idea of past work done in the field of desalination in chronological order. Also, there has been lots of study about the thermal analysis of a still experimentally and numerically. Then the gaps in the literature are discussed and from that objective of present work has been decided. This chapter gives the motivation behind this thesis work.

CHAPTER 3: Methodology is about the methods and models used to solve the current problem. This chapter describes various methods to solve a mathematical problem and various methods to analyze a process.

CHAPTER 4: Result and discussion describe the effect of various heat transfer coefficients on efficiency, the impact of water depth, wind speed, cover angle on efficiency. There is a detailed comparison between conventional and modified still with a PCM.

CHAPTER 5: Conclusion is about the summary of the present work and future scope of -the work.

CHAPTER-2

LITERATURE REVIEW

2.1 INTRODUCTION

Lots of work have been done in improvement in the efficiency of solar desalination processes. Many researchers have given correlations to find internal and external heat transfer coefficients for thermal analysis of solar stills. This chapter discusses the thermal analysis of solar stills (active and passive types) by various methods. There are parameters like water depth, preheating of feed water, slope angle, the gap between the water surface and glass surface, salinity of water, various meteorological factors which affect the efficiency of a still. One method to improve solar still's efficiency is to use phase change materials to provide thermal energy in non-sunshine hours.

2.2 CATEGORIZATION

The literature review is divided into two categories:

1. Theoretical analysis
2. Experimental analysis

2.2.1 NUMERICAL ANALYSIS

2.2.1.1 NATIONAL NUMERICAL STUDIES

Kumar *et al.* [9] did a thermal analysis of passive and active solar still for a given range of Grashof numbers. The model was based on the study of regression. For a given experimental data value of constants named C and n calculated. It was found that generally for passive solar still, C= 0.03220, n= 0.41140 and for active , C= 0.03220, n= 0.3830 is proven good. By mathematical modeling, it was well-validated with output error within the range of 14 %. it was also noted that productivity of passive still drops badly in the evening time as compared to active solar still.

Kumar et al. [10] studied for the annual output of active still in his article. An analytical expression for temperature and yield of water and glass cover were developed taking into account the design and climatic parameter. It is been noted that for given parameters, the optimum yield is for collector angle 15 ° and cover inclination is 15 °. It was also observed that maximum yield occurred between April and October months as more number of clear and sunny days. Low amount distillate was observed on rainy days because of the low value of solar insolation. Effect of water depth also observed as the amount of distillate output decreases with increasing depth because of storage effect.

Singh *et al.* [11] studied monthly efficiency with both passive and active type stills for various climatic conditions in India. Numerical calculations were conducted for New Delhi, Jodhpur, Chennai and Mumbai climatic circumstances for the hourly difference of average solar irradiance. The assumption was taken as quasi-static steady state. On the basis of theoretical investigation, it was found that the annual yield substantially depends on water depth, condensing cover tilt and collector angle for both passive and active solar stills. it was noted that annually yield for a given water depth increases linearly with active solar still collector area.

For condensing cover inclination it was observed optimum angle found nearby the latitude of a given place. The low value of distillate output between the month of November and February because of the less dollar irradiance.

Tiwari *et al.* [12] have evaluated a review work on solar desalination, for example, its present status and its future scope. The present study additionally incorporates water resource availability, water-demand, accessibility of consumable water and its filtration techniques including the condition of craftsmanship and authentic foundation. The characterization of disinfecting units has been done based on works explored until today. Concept of heat and mass transfer applied in the solar distillation process. The current status of solar-powered distillation units in India, single slope and double slope still are popular and increasing by time. This process is more popular in the middle east, especially in Saudi-Arabia. In his current study use of fiber-reinforced plastic in stills also discussed in brief.

Dev *et al.* [13] studied the characteristic equations and validate them with experimental data. For a different angle of tilt for glass cover (15°, 30°, 45°) readings were taken for climatic conditions i.e for winter and summers. It was noticed that solar still with an inclination of 45° gave the best results for both winter and summer. Also, the optimum angle was found 30° for different water depths (0.04, 0.08, 0.12, and 0.16 m) for the summer season. From the analysis of data lower water depth gives the best performance for a still. The optimum basin water depth (0.04 m) suited best for higher yields among distinct water depths because of low storage effect. However, it suggested 0.01m for tilt 15° for efficient operation. The developed characteristic equations give a relationship between parameters that predicts output like basin temperature, glass cover temperature for input parameters as ambient temperature and solar radiation. By putting values of these parameters one get an idea of best possible still in given conditions and also can save the cost of manufacturing.

Kumar *et al.* [14] investigates the H.T coefficient and fractional energy for single slope hybrid (PV/T) active type solar still and gave relation to finding out basin water temperature and glass cover temperature with less error with experimentation data. He also suggested that operational parameters like water depth affect the efficiency of a still badly.

Madhlopa *et al.* [15] investigate in his study about the view factor or shape factor for a solar still. Comparison in the study with and without taking the effect of shape factor into account showed a noticeable variation in result. The mode of heat transfer which affects the most is radiative heat transfer. This shows that radiative heat transfer has significant value to change the resulting output. The correlation used here for analysis was an empirical relation suggested by previous researchers. value of radiative heat transfer is directly proportional to the area of the projected surface. More of the area more would be its value.

Panchal *et al.* [16] in this paper discussed various methods to improve the production of freshwater from a solar still. Various methods like the use of fins, energy storage materials like PCM and multi-basin solar still have discussed. All of these methods improve the performance of still by a significant margin. Fin increases the surface area of basin water so as to improve the evaporation rate inside still. Energy storage materials stores energy by latent heat or sensible heat absorption and releases heat at night time when the energy needed for a solar still. In the multi-basin solar still, the heat of condensation of lower basin uses to heat above basin water and process repeats till top basin. So combining all above methods together results in increases in distillate production and resultant can be used for industrial as well as for household purposes.

2.2.1.2 INTERNATIONAL NUMERICAL STUDIES

Mousa *et al.* [17] studied on simulations of three distinct kind stills and of their year-round comparison of yield in Oman (Marmul). Three types of stills are regenerative, conventional, and still with double-glass-cover cooling. Certain parameters were also explored for their effect on the yield, i.e. bottom loss of basin, The regenerative still output exceeded the standard yield by 70%. If the stills are perfectly shielded, the conventional still had greater yield than the double-glass-cover cooling. Increasing the water depth in the lower basin reduced the yield of the 3 stills. Increasing the thickness of water film on top of the bottom glass did not affect the output of the still. It was observed among all the stills in given conditions regenerative still is best.

Torchia-Nunez *et al.* [18] give the idea of energy resources and their consumption closely relate to ecological development. Low consumption of energy yields high power output so as an increase in overall efficiency. Exergy analysis has been widely used in the imitation, design and enactment estimate of energy systems. The present study reviews exergy analysis and simulation of a wide range of renewable energy resources.

Khalifa *et al.* [19] did a theoretical approach to find out the effect operational, climatic parameters and design parameters on its performance to optimize the design. The cover tilt angle has a considerable effect on the still output. There is a number of repetition of trails to find out the productivity of a still in for distinct climates and tilt angle are discussed in this article. His findings suggest the value of the optimal glass cover angle. Modeling of a still gives the relation between the glass cover angle and efficiency of still in various climatic conditions. This paper helps to select the correct inclination angle in different latitudes and for different seasons. Also, increase with an increase in tilt angle would increase still output for the whole year. The study also suggests that the optimum glass cover angle coincides with the latitude of that place. So angle should be increased as variation in latitude takes place to have optimum production of distillate.

Dashban *et al.* [20] investigate the effect of paraffin wax when used as thermal storage for a solar still. It was a theoretical investigation to find out the performance of still kept under observation from morning 7.00 pm to 9.00 pm. To get thermal heat from paraffin wax, the mass of 18 k.g with 2 c.m thickness were used under the absorber plate for a continuous supply of thermal energy during night time. Also theoretical model developed with and without PCM to compare the experimental data with theoretical data. Heat transfer coefficient was computed from data (exp) as the empirical relations were giving an error. Parameters like glass cover temperature, basin water temperature, water depth were modeled to give distillate output. It was concluded from results that heat transfer coefficient plays an important role in the theoretical investigation. So it should be calculated from experimental data. Using empirical relation tends to give huge error while validating with experimental data. Also with enhancement in water thickness, the performance decreases as the specific heat of the water and the reduced air gap between the basin water surface and the glass cover temperature.

Setoodeh *et al.* [21] did a study using a CFD technique for single slope solar still. Software was used to perform analysis. A mixture of liquid and vapor simulated in 3D, mixture flow is also known as two-phase flow. They concluded that previous numerical studies show a considerable error in the temperature of water and glass. This model shows good agreement with experimental data considering fewer assumptions.

Ahsan *et al.* [22] studied the techniques to lower down the cost of solar-based desalination system saline water into potable water using solar energy. For cheap, lightweight, local and available materials triangular solar still was designed and fabricated. A delay of one hour or one and half hour for attaining peak value of solar insolation and ambient air temperature. Using an analytical approach a mathematical model was generated to establish a relationship between still output, basin temperature, glass cover temperature, water depth in still basin and many more parameters. Some correlation also formed using extracted data.
Performance of still measured for different water depths with the climatic condition of Malaysia and a reverse relationship was established between them. With modification in the design of a still, it was concluded that depth of water, solar insolation, climatic conditions, design conditions, and operational conditions affects the performance.

Ahmed *et al.* [23] did a theoretical investigation with the distinct shape of a solar still. According to his findings, still with a modified shape like pyramid type gives maximum productivity due to more solar insolation for a given geometry. The other two stills was a double slope shaped and for reference a single slope passive type of solar still. The increase in efficiency was around 20% with modification in shape.

Pielichowska *et al.* [24] Studied phase change materials (PCMs) used for the storage of thermal energy as sensible and latent heat and supply heat when required. Solar power is available at free of cost and easily available so we can use PCM to store thermal energy from sun and supply in non-sunshine hours. Till now various type of PCM's have been discovered they are categorized in organic and inorganic type inorganic.

Understanding the charging and discharging mechanism of these types of materials are difficult to understand so recent research efforts to understand the mechanism and effective use of PCM material. Its applications are vast such as used in the medical industry, chemical industries also applicable in the automotive sector.

There is a need to standardize the use of PCM around scientific society as scientists and researchers follow their own standards while dealing with these materials.

Abdellatif *et al.* [25] performed a theoretical investigation on active solar stills The flow rate of water is controlled in such a way that it always attain desirable values. Thermal modeling of still gives the relation between basin water temperature, glass cover temperature, PCM temperature and also a mass of distillate formed. Quasi-steady

heat transfer assumption was taken to express the complicated heat exchange taking place in the system. Heat transfer correlation was used by assuming Dunkle's model. The relation between the convective heat transfer coefficient, the evaporative heat transfer coefficient were used to solve the problem. These equations were solved by using explicit approach and a program is developed in MATLAB. This study shows that water depth is inversely proportional to distillate output i.e for increasing depth distillate output decrease. It is followed by the heat transfer fluid rate. Results showed that wind velocity is also a factor to affect the distillate.

It is recommended to install still on elevated sites. Also, cost optimization was performed to justify the cost of solar still.

Kabeel *et al.* [26] did a theoretical cost analysis along with thermal analysis of a solar still. Different Phase change material, both organic and inorganic type were chosen according to their properties and cost. Organic PCM A-48 was proven to be the best choice among organic. As for the same cost, it possesses higher efficiency. Also among inorganic PCM Capric palmitic showed the best results for the given price. But the inorganic type of PCM are not the first choice as they possess a negative impact on surroundings. The thickness of PCM has no impact on the efficiency of solar still. So additional thickness is not suggested at the cost of increasing price especially for organic PCM's. Increase in productivity of still was around 92% for both A-48 and Capric palmitic.

2.2.2 EXPERIMENTAL ANALYSIS

2.2.2.1 NATIONAL EXPERIMENTAL STUDIES

Tripathi *et al.* [27] in his paper identified the impact of the coefficient of evaporative heat transfer an active type solar still in the summer climate. The results for 24 hr observation for distinct five water depth from 0.04 m to 0.18m, it was observed that still, output results high for a lower value of water depth.

Shukla *et al.* [28] Performed an experimental investigation with lauric (PCM) act as thermal storage for a solar still to find out the optimum thickness of PCM material and to determine the efficiency of solar still. Energy balance on different parts of still are used to predict the temperature of basin water, glass cover temperature, distillate output. It was noticed that a higher amount of PCM (mass of PCM) when used with a low amount of water, the efficiency of still increases. Also, distillate output when using in the night with PCM can enhance by 130% and 31-36% respectively than without using PCM. Also, inner glass temperature is well predicted by relation developed using mathematical equations.
There is an increase in efficiency of still by 35% for still equipped with PCM.also as PCM kept below absorber plate so bottom losses decrease in this case. Still, output decreases when the depth of water in the basin decreases. At night time due to the availability of heat from PCM, still, output increases effectively.

Srivastava and Agrawal *et al.* [29] analyzed the impact of an absorber material on the performance of a basin type still. Jute absorbers are used here to increase evaporation inside still. It was also observed that high values of heat transfer coefficients with new modification were obtained. It concludes that increasing absorptivity in basin water increases the overall distillate without and the method selected above is cost-effective too.

Samanchi *et al.* [30] performed an experiment for conventional and modified still with PCM(phase change material). It is known that the solar distillation exhibits considerable economic advantages over the other water distillation processes as its less in cost, free energy available and reduces operational costs. Among selected energy storage materials, (MgSO4

7H2O) appears as the most efficient one to produce more still output is given the same conditions. So modified stills with PCM are generally more efficient ones than other modifications in still but the problem with them is to understand their phase change mechanism which is complex in nature.

2.2.2.2 INTERNATIONAL EXPERIMENTAL STUDIES

Zurigat *et al.* [31] studied a regenerative type solar distillation unit where the unit was designed theoretically and assessed its efficiency. The partition consists of 2 basins for inflow and outflow for double effect. It is to provide the facility to increase the temperature difference between the water surface and inner glass cover and utilizes the latent heat of water vapor condensing on the glass cover to take away heat by water flowing over the glass cover. The efficiency of the regenerative still was evaluated by comparing with the capability of the conventional still for same input conditions. after comparing the yield of both stills, the regenerative still was 20% more than the conventional still. the stills absolutely insulated increases their yield two and half folds. Insulated stills have a very high influence on the regenerative still than the conventional still. The wind velocity has a substantial effect on the yield of the stills. It can escalate the output by more than 45% if the wind velocity was increased from 0 to 10 m/s up to a particular time of a day as in evening time it reverses the nature by decreasing output by decreasing the output. The thickness of water mass on glass cover has no significant effect on productivity as far as only thickness and water mass is a concern.

Velmurugan *et al.* [32] in his paper he showed that on increasing the evaporation area of the still basin water, by using fins at the basin of the still productivity of still increases. sponges were used to increase exposed area so as to increase so as to enhance productivity. simple basin type still and still with wicks were studied experimentally. The equation governing the energy balance were solved theoretically and compared to experimental outcomes. The observation was that it was around 30% yield raised when wick type still was used, around 15% boosted when sponges were used and 45.5% increment was seen when fins were used. A good agreement can be seen with theoretical and experimental data.

Abdallah *et al.* [33] in his study found that the research reveals that the addition of absorbing material was certainly a good idea in enhancing the effectiveness of a still as raising its collection. Using metallic wiry sponges there were increases in distillate output around 30%

and 44% respectively. Drawbacks noticed with them as that it faces the problem of corrosion in some area of sponge. The reason for this is due to an increase in salt deposits after evaporation of water. Whereas black rocks face no corrosion problem and gave around 60% gain . also black rock possesses zero cost for the amount it was used interestingly so it's a very good option to use against other heat-absorbing arrangements. So, it can be wrap up with results that the black rocks absorbtivity, storing capacity and releasing heat during non-sun shine hours is better than the metallic wiry sponges and can improve output the productivity by nearly 21%. Its availability is good and it's cost-effective too.

Murugavel *et al.* [34] build a double slope still, the material used to built te still was mild steel sheet plate and experimented to find still effectiveness for different water depth, still with distinct bed materials, phase change materials. He concluded that quartzite rock is an effective basin material with the highest productivity. Basin material which absorbs heat energy results in bad efficiency. His experimentation also suggests for optimum layer thickness for a phase change material when used below an absorber plate.

Tigrine *et al.* [35] studied on double slope solar still was constructed. In its experimental process, several internal and external parameters were evaluated and observed under the daily varying condition from morning to evening. The external parameters like wind velocity increase distillate output to some extent to 3 pm afternoon then its effect reverses. Because of convection heat transfer increase inner glass cover temperature as well as basin water temperature decreases. Peak values of solar irradiance in afternoon supports increasing wind speed. The average production of distillate produced by solar desalination was around
4 L/ m^2.day.

Gugulothu *et al.* [36] in his study he discussed the use of PCM in solar still and discuss the scope of solar energy that its abundant and never lasting, free of cost and environment-friendly. Solar distillation provides a solution for small communities who faces problems with the scarcity of freshwater. For experimentation a single slope basin solar still with external thermal storage (PCM) used. Three different phase change materials were (Magnesium Sulfate Heptahydrate ($MgSO_4$ .7H_2O), Potassium dichromate (K2Cr2O7) and sodium acetate (CH3COONa) are used. Their data were compared under the same condition during a fix time interval. ($MgSO_4$ .7H_2O) proven to be the best option among all. By using these external sources for heating during non-sun shine hours increases the still output as a process can continue for up to 24 hrs. Value of solar insolation gets maximum at 1 pm but the temperature of basin water, glass cover reaches its maximum value at around 3 pm. Hence maximum distillate produced during these hours.

Kabeel *et al*. [37] studied a modified system experimentally to see the effect on the productivity of a still. This modified still consisting a PCM with an injection to inject hot air inside still. Data for both still, conventional type and modified one compared under the same atmospheric conditions. Results showed that the production of distillate reaches to 9.36 (L/ m^2 day). So comparative study showed that enhancement in freshwater productivity with a modified still consisting PCM and a hot air injection. The experimentation was carried out under the same climatic conditions. It was observed that the modified still was able to deliver 108 % more distillate than conventional solar still. It was conducted in the month of July 2015 in Egyptian conditions. The duration of observation was from 6.00 am to 10.00 pm. Impact of hot air injected on still was to increase the evaporation rate. PCM was used as thermal storage for non-sun shine hours.

Abu Arabi *et al*. [38] investigated both theoretical and experimental study on active solar still with PCM to provide thermal energy to still in the night time. There was excellent agreement shown with theoretical and experimental data. While increasing water mass keeping PCM mass fixed up to 1: 10, then there was a reduction in productivity by up to 30%. It was well proven that these type of arrangement with such modification gives better performance as compared with conventional ones. The thickness of PCM does not play significant either cost-effective to use for a small increase in efficiency. External heating like using the solar pond and shallow pond also create an option to increase in productivity. Good agreement obtained between the experimental and the theoretical analysis.

Also, the modeling of PCM material was a little difficult as the charging and discharging phenomenon mechanism were difficult to understand. This type of arrangement best suited for cold places as the ambient temperature falls during night time so temperature difference causes an increase in the distillate. Modification in stills is the current topic of research as freshwater is the need of the future.

Abu Arabi *et al.* [39] conducted experimentation on modified solar still with a phase change material at the bottom of an absorber plate and an external collector plate. The PCM stores thermal energy in the day time as latent or sensible heating in the day time and releases heat in the night time by latent or sensible cooling to ensure continuous operation. Basin water is heated with solar radiation directly and with hot water heat exchanger where hot water is supplied by an external solar collector. Water droplets after condensation collected a collector trough at sides of the glass cover. Obtained water is a pure form of water. The flow of hot water, condensate flow, amount of water in basin i.e basin water level studied. It was concluded that distillate produced was directly proportional to the rate of hot water circulated and the ambient temperature outside. The optimum value of the cooling water flow rate was about 10 ml/s. also, the effect of water depth was observed as the amount of distillate produced decrease as water depth in basin increases. The modified still has produced of which around 40% was produced after sunset. In this study economic analysis shows that it is cost-effective and can be used in a remote area where the availability of freshwater is a big problem.

Yousef *et al.* [40] did an experimentation analysis to study heat transfer characteristics of the PCM storage unit, its applicable to the solar still. Fin type arrangement enhances the thermal conductivity of PCM. Three still were studied to do experimental analysis. Conventional still, solar with PCM and solar with the fins heat sink. The results showed that PCM affects the output in day time but for night time when the sun is not available then it performs well and overall its increases efficiency. Finned fin equipped still performed best among all. It was noticed that the third type of still was the most efficient one. However, the margin in efficiency was not exceeding 8% for the second type as compared to the third type.

Cheng *et al.* [41] performed both experiment and simulation to evaluate the productivity of a solar still with new modification by adding SSPCM (shape-stabilized phase change material). This PCM possesses good thermophysical properties. It was noticed during experimentation that thermal conductivity of PCM was 1.50W/mK and its absorption coefficient was 0.94 which was higher than the absorptivity of absorber plate. After experimentation mathematical modeling established between basin water temperature, glass temperature, PCM temperature, distillate output e.t.c. Experimental results showed that there was an increase in productivity using modified still was 43.30 % and distillate output was 3.41 L/m^2 higher than the conventional still. There was an increase in melting point from 34 °C to 50 °C and with this productivity, the increase was from 21.5% to 57.5%. Overall shape stabilizes technique has an advantage. By economic study also proves its acceptability and its high absorptivity also gives solution to the absorber plate.

2.3 GAPS IN THE LITERATURE

i. Limited work using numerical methods for conventional stills.
ii. Limited studies on the behavior of a phase change materials which shows a rate of change during charging and discharging process.
iii. Effect of various design, operational and meteorological parameters together in details.
iv. Only a few studies show the effect of thickness of thermal storage taken in a night time.

Limited research on the organic and inorganic type of PCM and their cost-effectiveness.

2.4 THESIS OBJECTIVES

The present work investigates the study of various input parameters for a conventional type of solar still. Then follows the study of modified still consisting of external thermal storage. Following are the specific objectives of the thesis:

i. Theoretical investigation of a conventional type of solar still and studying various factors affecting its efficiency. Parameters like water depth, the effect of slope angle, wind speed which affect the efficiency of a still.
ii. Investigation of the efficiency of a single slope passive type conventional still and modified still under the same input conditions. Comparing their productivity, heat transfer coefficients in details.
iii. Investigating the effect of thickness of paraffin wax and comparing efficiency for a different type of phase change materials and predicting the optimum one for general use.

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CHAPTER-3

METHODOLOGY

3.1 INTRODUCTION

In the present work, a comprehensive theoretical model is developed to evaluate the distillate output for a conventional still. Principle of heat transfer and balancing energy equations that govern the working of single slope solar still. A mathematical model is developed to analyze the thermodynamic behavior. In this model, critical parameters such as water depth, solar irradiance, wind speed, cover angle, and simulation had been done. results reveal the importance of latitude with glass cover angle, increasing water mass i.e the water depth decreases the output, also the wind speed increases the output with some conditions else decreases the distillate output. Then the model is modified as a solar still equipped with a PCM (to provide thermal energy to basin water in night time). the effect of modification on solar still with PCM and its effect during non-sun shine hours have been reported. Paraffin wax has been a popular choice for selection of a PCM due to its availability and cost-effectiveness. Theoretical calculations showed that there is a significant enhancement in distillate output when an external source applied to the conventional arrangement. Before proceeding to study modified still there are several parameters are to study as the heat transfer coefficient for various ambient conditions. Study of climatic parameters such as the effect of solar radiation, wind speed, ambient temperature, outside humidity e.t.c. after that study of operational parameters such as depth of water, preheating of water, the coloring of water e.t.c. design parameters such as insulation of still, cover angle, the orientation of still. Increase in run time for experiment results in more amount of distillate. Furthermore, the comparison between theoretical and experimental study approximates as specified in the literature review.

3.2 PHYSICAL MODEL

Figure (3.1) shows both stills, (a) conventional, (b) modified still with a PCM. In the present work, it is assumed that the depth of water is constant i.e 2 cm throughout the experimental process and the same assumed in theoretical modeling. The dimension of the bottom of still is 0.6x1.2 m^2 [44] and the thickness of paraffin wax assumed 3 cm. The side and bottom walls of the system are assumed to be insulated. Furthermore, solar irradiance falls on glass surface then transmitted rays partially gets absorb in basin water and finally absorb in absorber surface completely. Using PCM below the surface of the absorber plate though reduce day time efficiency but increases overall efficiency. Mechanism of charging and discharging of phase change materials is a complex process so its a current area of research. Quantity and quality of solar irradiance assumed to be constant during the experiment and mathematical modeling.

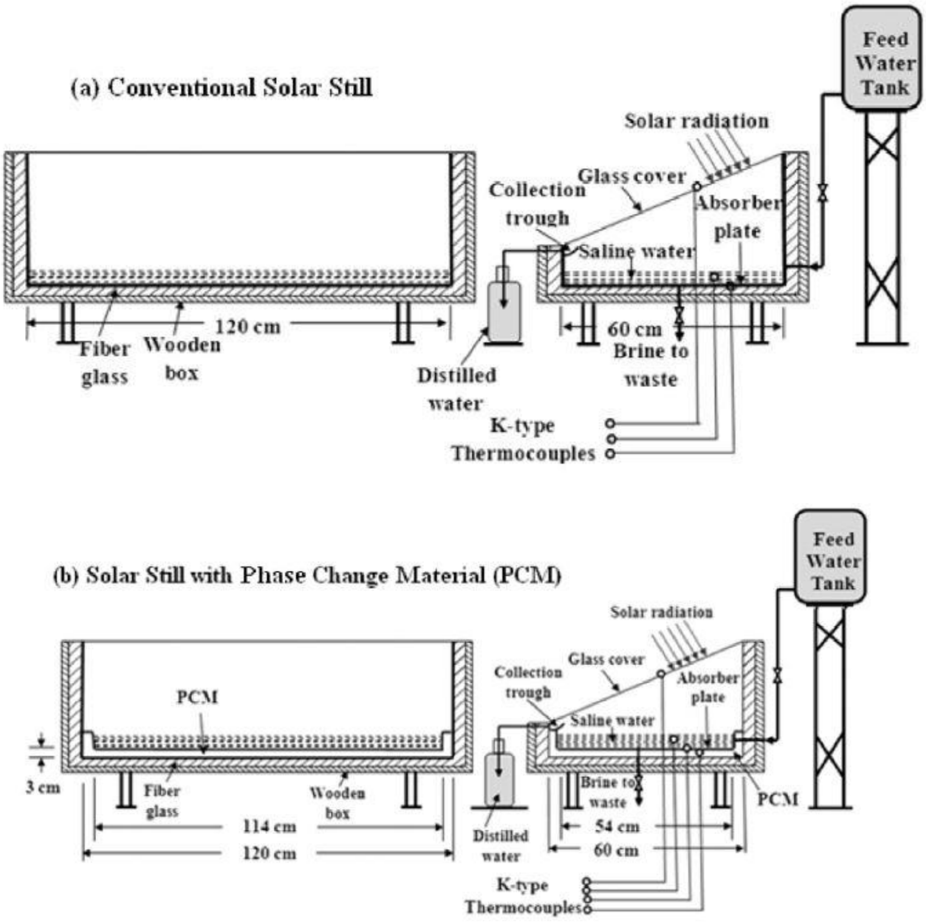

Figure 3.1 Solar Still without and with PCM [8]

3.3 ASSUMPTIONS

1) Inside of still assumed to be vapor leak proof.
2) Absorptivity of glass cover assumed to be very less.
3) The temperature gradient across the thickness of water and PCM is zero.
4) Thermophysical properties are taken at an average temperature of the water.
5) Problem is 1-D as there is a change in temperature with respect to time only.

3.4 MATHEMATICAL MODELLING

Mathematical models include a set of mathematical equations which describe the behavior of a system. In the present study, there are three sets of differential equations, which describe the working of a solar system physically. Energy balancing is done for each part of a still which interact with the sun directly.

The mathematical modeling of the solar still essentially involves the following steps:

1. Calculation of evaporative and convective heat transfer coefficients
2. Calculation of losses (external) from glass cover temperature.
3. Calculation of external losses of a solar still.
4. Input the meteorological condition.
5. Energy-absorbing mechanism of a PCM in a solar still
6. Solving all available equation with given values.

The computer program is written in MATLAB software. [45]

3.5 HEAT BALANCE

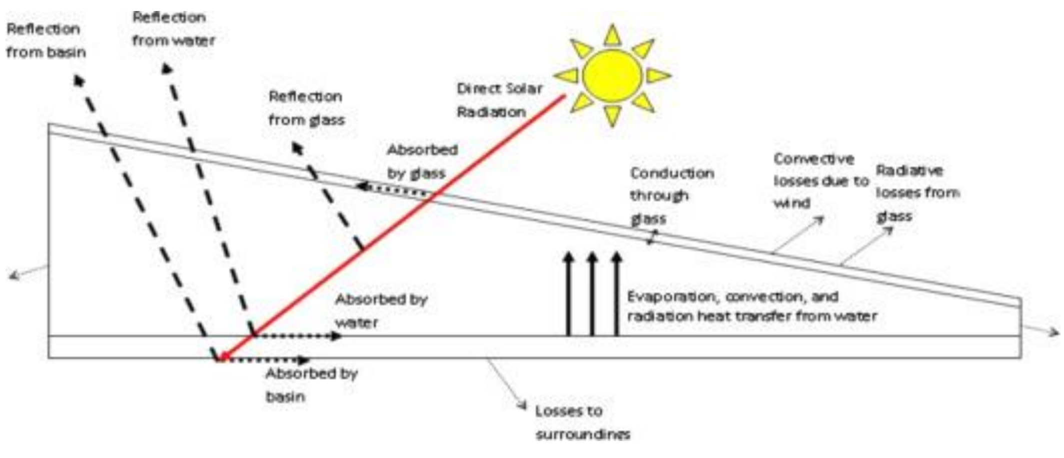

Figure 3.2: Schematic diagram of a single slope basin type of still [46]

Heat balance equation on basin water can be written as [47]

$$I\alpha_w \tau = q_e + q_r + q_c + q_b + C_w \frac{dT_w}{dt} \tag{3.1}$$

Heat balance on glass cover

$$q_{ga} + c_g \frac{dT_g}{dt} = I\alpha_g + q_e + q_r + q_c \tag{3.2}$$

Combining equation 3.1 and 3.2, we get

$$I\alpha_w \tau + I\alpha_g = q_{ca} + q_{ra} + q_b + C_g \frac{dT_g}{dt} + C_w \frac{dT_w}{dt} \tag{3.3}$$

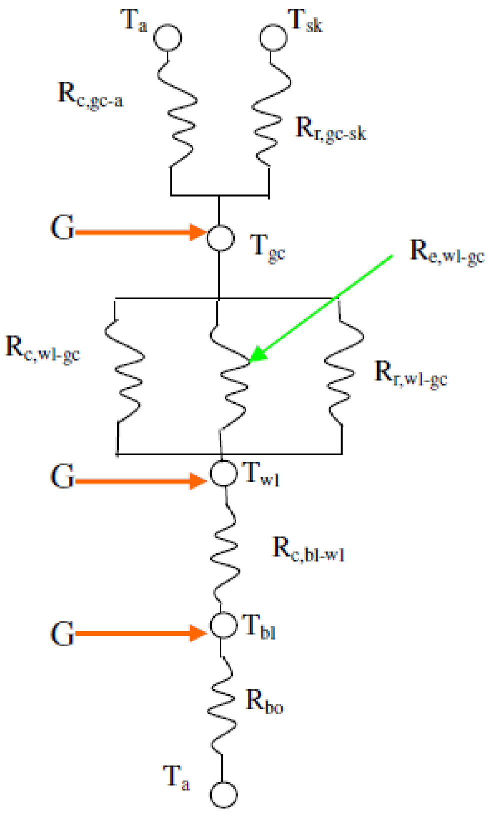

Figure 3.3: A thermal resistance network corresponding to the heat transfer [46]

$$q_r = F\sigma(T_w^4 - T_g^4) \tag{3.4}$$

Where

$F =$ View factor between two surfaces.

$\sigma =$ Stefan Boltzman constant.=5.67x10^{-8} (W/m^{2}K^4)

$$q_r = 0.9\sigma(T_w^4 - T_g^4) \tag{3.5}$$

$$q_c = h_c(T_w - T_g) \tag{3.6}$$

Where

h_c= convective heat transfer coefficient

$$h_c = 0.884\left[T_w - T_g + \frac{(P_w - P_g)}{268.9\times10^3 - P_w}T_w\right]^{1/3} \tag{3.7}$$

The empirical expression for q_e as given as [7]

$$q_e = 16.28*10^{-3}h_c(P_w - P_g) \tag{3.8}$$

$$q_b = U_b(T_b - T_a) \tag{3.9}$$

$$q_{ca} = h_{ca}(T_g - T_a) \tag{3.10}$$

Where

h_{ca} = convection heat transfer from glass to ambient

$$h_{ca} = 2.8 + 3.8\ V \tag{3.11}$$ [7]

Where

V= wind speed (m/s).

$$q_{ra} = \varepsilon_g\sigma(T_g^4 - T_s^4) \tag{3.12}$$

3.5.1 ENERGY BALANCE WITH ABSORBER PLATE

$$m_{abp}C_{P\ abs}\frac{dT_{abp}}{dt} = \alpha_{abp}A_{abp}I - Q_{b-w} - Q_b - Q_{b-PCM} \tag{3.13}$$

Heat transfer between basin plate and water is via natural convection process as

$$Q_{abp-w} = h_{abp-w} A_{abs\,plate}(T_{abs} - T_w) \quad (3.14)$$

$$h_{abp-w} = 0.54 \frac{K_W}{X'} [Gr * Pr]^{0.25} \text{ [44]} \quad (3.15)$$

$$\mathrm{Gr} = [\frac{\rho^2 g \, \beta_w \, (T_{abp} - T_W)[X']^3}{\mu_W^2}] \quad (3.16)$$

$$Pr = [\frac{C_P \mu}{K_w}] \quad (3.17)$$

3.5.2 ENERGY BALANCE IN SALINE WATER

$$m_w C_{P\,W} \frac{dT_w}{dt} = \alpha_w A_w I + Q_{b-w} - Q_{b-w} - Q_{w-g} - Q_{c(w-g)} - Q_{evap} \quad (3.18)$$

Assuming make water heat negligible for small depth process

$$Q_{c(b-g)} = h_w A_w (T_w - T_g) \quad (3.19)$$

Where

$$hw = 0.8840 \left[T_w - T_g + \frac{(P_w - P_g)}{268.9 \times 10^3 - P_w} T_w \right]^{1/3} \text{ [7]} \quad (3.20)$$

Where

$$P_w = e^{25.317 - (\frac{5144}{t_w + 273})} \quad (3.21)$$

$$p_g = e^{25.317 - (\frac{5144}{t_g + 273})} \quad (3.22)$$

$$Q_{w-g} = \frac{\sigma[(T_W + 273)^4 - (T_g + 273)^4]}{\left(\frac{1 - \epsilon_W}{A_W \varepsilon_W}\right) + \left(\frac{1}{A_g F_{GW}}\right) + (\frac{1 - \epsilon_g}{A_G \epsilon_g})} \quad (3.23)$$

$$Q_{evap} = (16.237 * 10^{-3}) h_{c(w-g)} A_w (P_W - P_g) \text{ [7]} \quad (3.24)$$

3.5.3 ENERGY BALANCE FOR GLASS COVER

$$m_g C_{pg} \frac{dT_g}{dt} = \alpha_g A_g I + Q_{w-g} + Q_{c(w-g)} + Q_{evap} - Q_{c(g-a)} - Q_{r(g-a)} \quad (3.25)$$

Where

$$Q_{r(g-a)} = \varepsilon_g A_g \sigma[(T_g + 273)^4 - (T_{sky} + 273)^4] \quad (3.26)$$

$$T_{sky} = T_a - 6 \quad (3.27)$$

$$Q_{c(g-a)} = h_{c(g-a)} A_g (T_g - T_{sky}) \quad (3.28)$$

$$h_{c(g-a)} = 5.7 + 3.8V_a \quad (3.29)$$

3.5.4 ENERGY BALANCE FOR PCM

Energy balance for absorber plate

$$I(t)\alpha_P \tau_g \tau_w = h_w(T_{abs} - T_{PCM}) + \left(\frac{k_{PCM}}{X_{PCM}}\right)(T_P - T_{PCM}) + \left(\frac{m_p C_p}{A_P}\right)\left(\frac{dT_P}{dt}\right) \quad (3.30)$$

Energy balance for phase change material(PCM)

$$\left(\frac{K_{PCM}}{X_{PCM}}\right)(T_P - T_{PCM}) = \left(\frac{k_{ins}}{X_{ins}}\right)(T_{PCM} - T_a) + \left(\frac{M_{equ}}{A_P}\right)\left(\frac{dT_{PCM}}{dt}\right) \quad (3.31)$$

M_{eq}= Equivalent heat capacity of a PCM

$M_{eq}=m_{pcm}c_{s,PCM}$ *for* $T_{PCM}<T_m$

$M_{eq}=m_{pcm}L_{PCM}$ *for* $T_{PCM}=T_m$

$M_{eq}=m_{pcm}c_{l,PCM}$ *for* $T_{PCM}>T_m$

3.6 HEAT TRANSFER WITH IN A PCM

The PCM can be used as thermal energy in case of non-availability of thermal energy. At the time of charging of PCM, heat is given and it stores heat as sensible heat until its melting temperature. Then latent heat absorbed by PCM at a constant temperature. Often its called latent heat of fusion. Then again sensible heat storage for phase change material till the maximum temperature of absorber plate. Then in non-sun shine hours particularly in the night, it releases heat in three consequent steps as discharging in sensible (liquid)zone, releasing latent heat of fusion, then sensible heat(solid) release about the ambient temperature in night.

3.7 METHOD TO SOLVE A MATHEMATICAL PROBLEM

For modeling of Systems and Components in engineering design, there are few approaches as follows-

3.7.1 PHYSICAL MODEL

These are the real system that worked in actual condition to give actual data output and analyses the performance of the system. This prototype can be constructed of the actual size or of reduced size. Usually, a descaled model is prepared to get the idea of initial working conditions or to obtain some preliminary design data. After the initial stage succession fully-fledged model is constructed to get the idea of actually working condition in given circumstances. This kind of models is not always possible in some cases where it's not cost-effective. There is also in some certain condition model works appropriately but in some different conditions, its working affects badly.

3.7.2 MATHEMATICAL MODEL

It represents the behavior and performance of a system in which mathematical equations predict the phenomenon. These are quite flexible in the design process. Once a mathematical model is made then the whole model is analyzed with given input conditions. This makes the simulation and optimization easy for a given system.

3.7.3 NUMERICAL MODEL

These models are used where the traditional methods fail to give a solution. These models are popular in engineering problems and most of the problems solving in today’s time are via numerical techniques. these are conventionally based on the discretized form of system. Most popular techniques are using FEM, FVM and CFD simulations. In numerical models, the system is broken in tiny parts and solve for each part one by one in continuation. This simulation gives a better idea for system solution but system require some time to solve the problem if the fine-meshed system.

One of the explanations suggests that analytical methods give exact solutions while numerical methods give approximate solutions. Examples are as Taylor series expansion and even Picard's successive approximations are all numerical methods. They all give a solution with some error. Actually in this case almost all methods - except very few ones - are numerical.

Also, another explanation suggests that the difference is that an analytical method gives an accurate closed-form of solution. A numerical method gives a solution at given points only. Methods like the finite difference method and finite element methods are numerical since they give results at certain points.

Most of the engineering problems are based on numerical methods as analytical method gets complex with the increase in the number of variables and derivative and integral terms.

In present work, mathematical modeling is used to predict the performance of simple basin solar still. Mathematical equations that describe the performance of each component of the system are presented in this chapter.

3.8 METHOD TO SOLVE CURRENT PROBLEM

3.8.1 Analytical method: by solving equation no 1, 2, 13 and substituting T_g and T_b in equation 2, we get a first-order ordinary differential equation.

$$\frac{\partial T_w}{\partial t} + aT_w = f(t) \qquad (3.32)$$

$$a = \frac{U_L}{mc_w} \text{ , } U_L=U_B+U_T$$

$$U_B = \frac{h_w * h_b}{h_w + h_b} \text{ , } \quad U_T = \frac{h_{1w} * h_{1g}}{h_{1g} + h_w * \cos(\beta)}$$

$$f(t) = \frac{\alpha_w * \tau_g * I(t) + \frac{h_w * \alpha_b * \tau_g * \tau_w}{h_w + h_b} * I(t) + \frac{h_{1w} * \alpha_g * I(t)}{h_{1g} + h_w * cos(\beta)} + U_L * T_a}{mc_w} \qquad (3.33)$$

After solving differential equation (32) for time interval Δt

We get

$$T_W(i+1) = \frac{f(t)}{a} * (1 - \exp(-a\Delta t)) + T_W(i) * \exp(-a\Delta t) \quad (3.34)$$

$$T_G(i+1) = \frac{\alpha_g * I(t) + h_{1w} * T_W(i) + h_{1g} * T_a}{h_{1g} + h_w * \cos(\beta)} \quad (3.35)$$

Value of Tw and Tg are sufficient to predict distillate output.

3.8.3 Numerical method:

At first iteration time temperature of glass cover(inner glass cover, water temperature, absorber plate temperature, PCM temperature are taken as an ambient condition then by solving equation (3.13, 3.18, 3.25 and 3.30) are solved to get the values of above unknowns as follows-

$$T_g(i+1)=T_g(i)+dt_g \quad (3.36)$$

$$T_w(i+1)=T_w(i)+dt_w \quad (3.37)$$

$$T_{abp}(i+1)=T_{abp}(i)+dt_{abp} \quad (3.38)$$

$$T_{PCM}(i+1)=T_{PCM}(i)+dt_{PCM} \quad (3.39)$$

Modified Euler's method with second-order accuracy is used to solve equation (3.13, 3.18, 3.25, and 3.30). It’s also known as backward difference implicit type technique.

CHAPTER -4

RESULTS AND DISCUSSION

4.1 ESTIMATION OF CONVECTIVE HEAT TRANSFER COEFFICIENT IN A SOLAR STILL

Internal heat transfer coefficient plays an important role as transportation of pure water from the basin and leaving dirt left in still basin. [9]

$$q_c = h_c * A_b * \Delta T \tag{4.1}$$

$Nu = h_c / (k/d)$. (4.2)

$Nu = C(Gr \times Pr)^n$ (4.3)

C = 0.0322; n = 0.4114 for Grashof no. Range: $1.794 \times 10^6 < Gr < 5.724 \times 10^6$.

Computed and experimental relation for a single slope passive type of still describe the trend Of the parameter mentioned in table 4.1 and 4.2 briefly.

Table 4.1 Comparison between experimental and theoretical data for single slope passive solar still

Sr.no	Experimental output in (ml)	Theoretical output in (ml)	Convective H.T.C h_{cw} ($W/m^2.K$)	Evaporative H.T.C hew ($W/m^2.K$)	Error (%)
1	130	124.31	2.2976	16.47	-4.37
2	232	258.20	2.73	23.31	11.29
3	360	384.08	2.95	30.34	6.68
4	320	311.88	2.79	28.04	-2.53
5	285	249.89	2.66	24.54	-12.31
6	200	179.72	2.46	20.80	-10.13
7	100	85.57	2.16	12.65	-14.42

Table 4.2 Experimental reference for a solar still on a hot summer day

Sr.no	Time of day (24 hrs)	Tw (^oC)	Tg (^oC)	Ta (^oC)	Experimental output (ml)
1	10.00	45.8	40.8	38	130
2	11.00	50.6	43.5	39	232
3	12.00	55.6	47.3	42	360
4	13.00	54.6	47.3	42.5	320
5	14.00	52.3	45.6	42	285
6	15.00	49.8	44.1	41.50	200
7	16.00	41.1	36.6	41	100

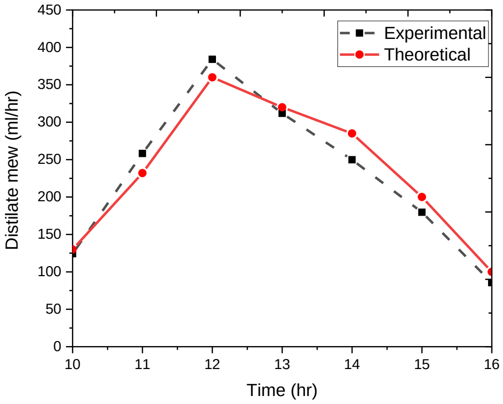

Figure 4.1 Hourly yield comparison for experimental and numerical analysis

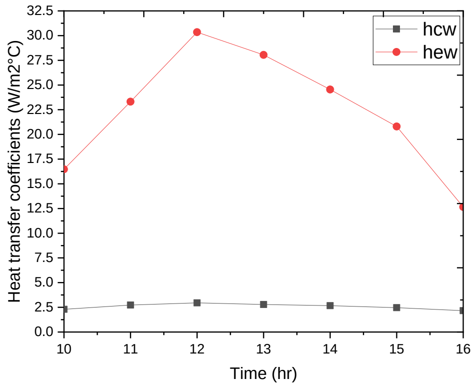

Figure 4.2 Hourly comparison between convective and evaporative heat transfer coefficients

Based on the above results shown in Fig 4.1 and 4.2 it can be seen that theoretical and experimental results good agreement using given values of C and n for a given hot summer day of Delhi. The error was within 14.42% for the given time interval.

4.2 EFFECT OF DEPTH OF WATER IN SOLAR STILL PRODUCTIVITY

In general higher the volume of water in basin higher heat required to raise the unit temperature of the water. It means higher the heat-storing capacity of a still.

In a passive type of solar still, lower the depth faster would be a rise in temperature and higher the evaporation consequently higher the productivity as less heat storage in still.

As per the literature review for passive type single slope solar still, the water depth range varies from place to place as regress experimentation by researchers [7]. A water depth of 7.60 cm is suitable for a still having a thermal capacity of 1.41 KJ/m^2 i.e typically in Australian condition for still with bottom insulation. Water depth of 2.54 cm is more suitable for a solar still resting on the ground without any insulation in general condition.

Here in this section data is taken from Tripathi [28] experimentation for new Delhi condition for a day of December month for validation of the mathematical model.

Table 4.3 Comparison between theoretical and experimental output values for a single slope passive type still for water depth=0.05m

Time (hr)	I(t) (W/m^2)	Ta (°C)	Mew(exp) (kg/hr)	Mew(theo) (kg/hr)
9	369.78	15	0.01	0.0167
10	570.56	16	0.0109	0.04075
11	657.85	18	0.021	0.08642
12	724.86	20	0.056	0.1159
13	658.04	22	0.108	0.1296
14	456.53	23	0.128	0.1294
15	324.28	24	0.100	0.1164
16	117.59	23	0.082	0.0977
17	0	22	0.064	0.0690
18	0	20	0.053	0.0599
19	0	17	0.042	0.0527
20	0	16	0.032	0.0508
21	0	16	0.028	0.0404
22	0	16	0.025	0.0354
23	0	16	0.20	0.0302
24	0	16	0.016	0.0281

Table 4.4 Comparison between theoretical and experimental output values for a single slope passive type still for water depth=0.10m

Time (hr)	I(t) (W/m^2)	Ta (°C)	Mew(exp) (kg/hr)	Mew(theo) (kg/hr)
9	392.46	14	0.016	0.03621
10	569.78	18	0.037	0.04612
11	680.26	20	0.052	0.0530
12	701.16	22	0.058	0.0590
13	625.31	25	0.057	0.0609
14	571.27	24	0.053	0.0550
15	399.73	23	0.044	0.0500
16	140.97	23	0.038	0.0440
17	0	18	0.031	0.0397
18	0	15	0.026	0.0330
19	0	13	0.020	0.0300
20	0	12	0.016	0.0264
21	0	12	0.013	0.0230
22	0	11	0.010	0.0210
23	0	10	0.009	0.0209
24	0	9	0.008	0.0198

Table 4.5 Comparison between theoretical and experimental output values for g a single slope passive type still for water depth=0.15m

Time (hr)	I(t) (W/m^2)	Ta (°C)	Mew(exp) (kg/hr)	Mew(theo) (kg/hr)
9	391.80	16	0.010	0.02626
10	569.41	19	0.03379	0.3494
11	679.65	20	0.03399	0.04591
12	723.17	22	0.0458	0.04683
13	681.86	22	0.4226	0.04524
14	569.41	22	0.40	0.04273
15	321.30	20	0.036	0.03966
16	140.67	14	0.03452	0.03681
17	0	13	0.03167	0.03465
18	0	12	002905	0.03191
19	0	10	0.02609	0.02815
20	0	10	0.0222	0.02599
21	0	9	001732	0.0236
22	0	9	0.01526	0.02109
23	0	8	0.01185	0.01927
24	0	8	0.00991	0.01787

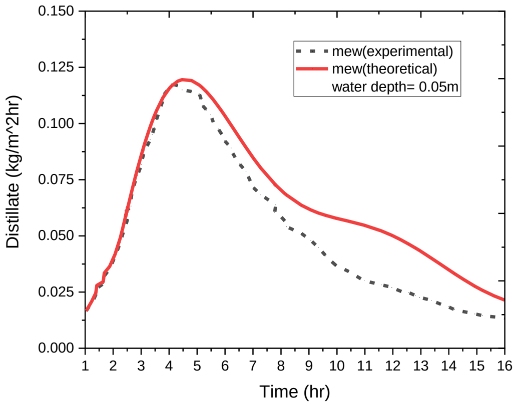

Figure 4.3 Hourly variation of yield for water depth of 0.05m

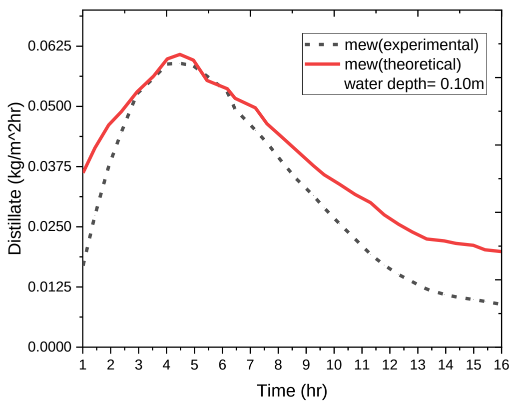

Figure 4.4 Hourly variation of yield for water depth of0.10m

Figure 4.3-4.5 show good agreement with experimental data. However, in non-sunshine hour variation difference is large (mention max deviation % in bracket). This could be because of variation in wind speed, losses in winter is higher due to low-temperature ambient conditions.

Figure 4.6 shows the variation in convective heat transfer for different water depth. Higher the value of the internal heat transfer coefficient higher is the value of distillate production. A low value of h_c shows that transportation of bulk due to buoyancy forces arise because of density difference in space is low that is why lesser productivity. The peak value of h_c is 2.51163 W/m^2°C for 0.05m water depth and 2.02717 W/m^2°C for water depth 0.15m for same given ambient conditions.

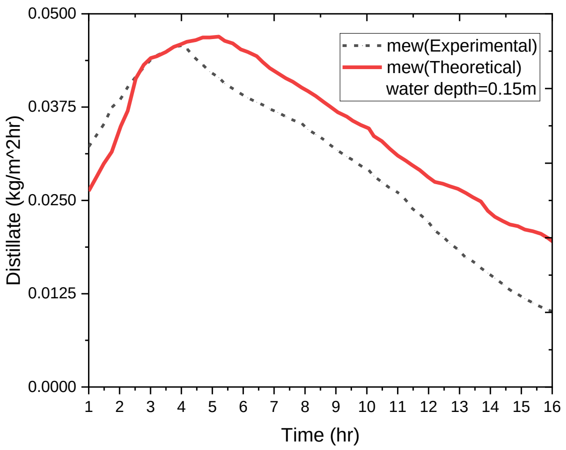

Figure 4.5 Hourly variation of yield for water depth of 0.15m

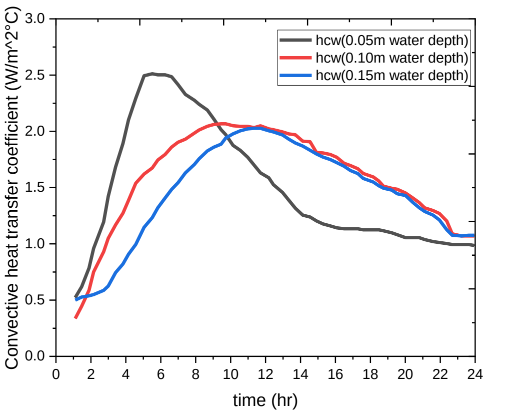

Figure 4.6 Comparison of convective heat transfer coefficient for different water depths i.e. for 0.05m, 0.10m, 0.15m respectively

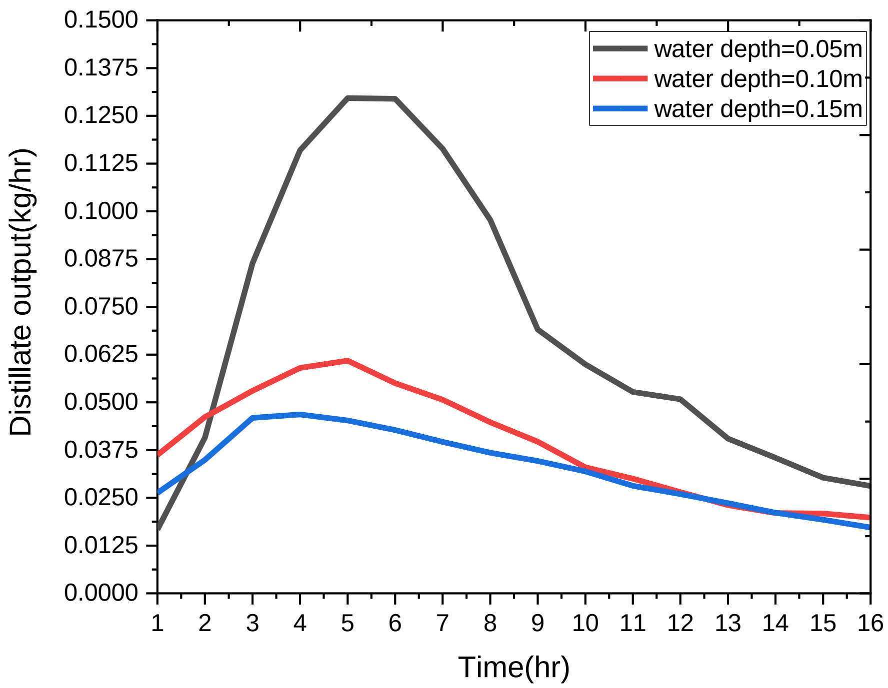

Figure 4.7 Hourly yield for different depth

Figure 4.7 shows that how variation of water depth badly affects the productivity of still. In peak hours for the same meteorological condition, there is loss up to 72.35% for this particular simulation and overall 48.19% increase in productivity with water depth 0.05m than a water depth of 0.15m for this particular winter day. It’s recommended that water depth should be in the range of 2-5 cm for maximum productivity and maintaining the same water level for the experimentation period**.**

4.3 EFFECT OF CHANGE IN GLASS COVER ANGLE

The best orientation of glass cover varies seasonal and also geographically for the same solar still. For getting the best efficiency from a solar still, glass cover angle should be optimized. It's observed from experimentation that in northern India best angle coincide with the latitude of the place [7]. But still, it varies seasonally. At any geographical cover, the angle should be minimum 10° so that water droplets should not fall. Also, it’s recommended that before assembling still inner surface should be clean to avoid condensate loss. In winter drinking water need is less as compared to summer.

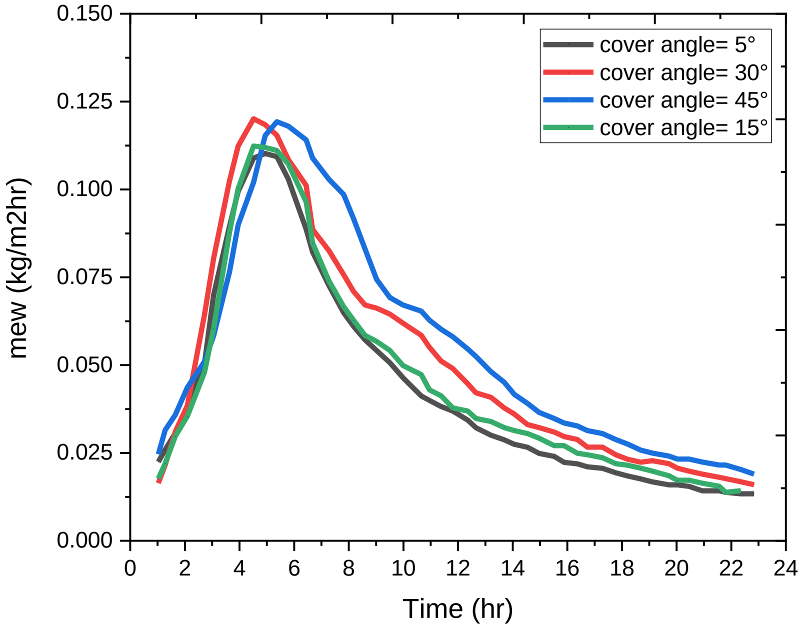

Figure 4.8 Variation of productivity for different glass cover angle

So still angle should be optimized for summers particularly. We generally use toughened glasses instead of plastic acrylic cover due to greater surface tension between condensate and plastic cover as compare to glass-water. For theoretical investigation data [28] is same as above taken for 0.05m water depth for Delhi winter conditions.

Figure 4.8 shows the variation for the different cover angle. The vertical axis shows distillate per m^2hr with a maximum of 0.1259 kg/m^2hr for an angle of 45°. It shows that for winter condition in Delhi optimized angle is nearby 15°. Minimum distillate output for 5° and for 45° it was maximum. Variation in productivity due to different angle in current simulation is 29.91%.

However in summers optimum changes due to higher ambient temperature and solar insolation. The trajectory of sunrise and sunset also changes. From the literature review, it was observed around 30° for New Delhi geographical location.

4.4 EFFECT OF CHANGE IN WIND SPEED

When still mounted, wind can flow over glass cover to increase losses to the surrounding. Generally, it considers that higher the wind velocity, higher the condensation rate over glass cover, higher the evaporation rate consequently higher the production of distillate. Generally, it's effective to lower depth of water, on optimum thickness it maximizes production. With a higher depth of water, it's effective up to peak sun intensity, in the evening time when solar energy is absent it reverses the effect. Generally change in efficiency is within 10% range for speed range 1-8m/sec.

heat transfer equation involves wind speed is

$$hcg=2.8+3.0*V \tag{4.4}$$

where V is wind speed in (m/sec)

hcg= convective heat transfer coefficient from outer glass temperature to surroundings

Solar insolation is observed for a time interval of 9 am to 7 pm evening. Solar peak reaches about 1020 W/m^2 at about 1 pm noon. Its tends to zero in 7 pm evening. Time interval of 1 minute is taken to do simulation. An analytical method is used to find a solution with $\Delta T = 60\ sec$.

Table 4.6 shows the initial values of temperatures, still properties to study the effect of wind speed. Figure 4.9 and 4.10 show the solar insolation and ambient temperature which is being curved fitted. These are input variables to determine the temperature of basin water and glass cover temperature which helps us to predict the value of distillate produced.

Table 4.6 Thermophysical and optical properties [50]

Parameters	values
Initial (t_{w0})	25°C
Initial (t_{g0})	28°C
Initial (t_{a0})	30°C
Absorbtance (α_b)	0.5
Glass absorbtance (α_g)	0.05
Water absorbtance (α_w)	0.01
Glass emissivity (ε_g)	0.84
Water emissivity (ε_w)	0.95
Water mass	3 kg
Cover angle(β_c)	10°
Basin area	1 m^2
Simulation time	600 min

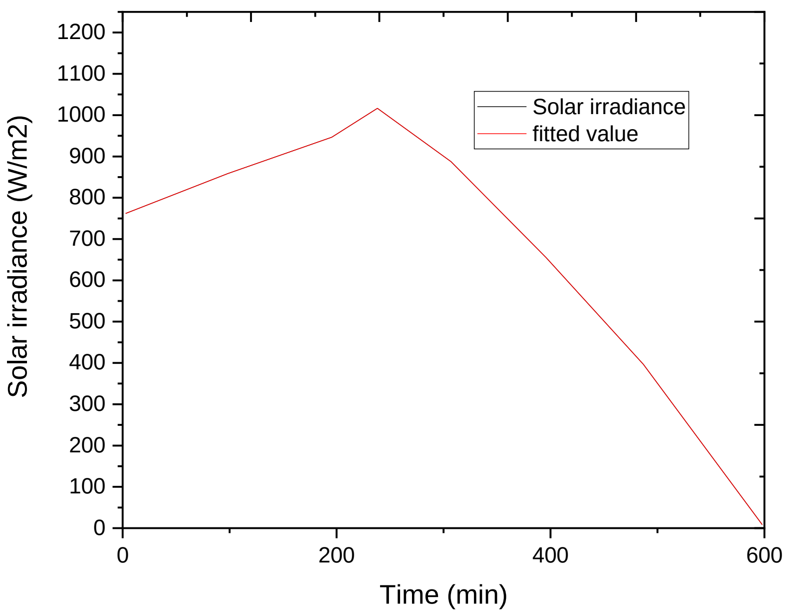

Figure 4.9 Input solar insolation variation

Figure 4.9 shows solar insolation is being curve fitted as per following equation-

$$J(i)= 760+35.52505*i-0.85666*i^{2}+0.00796*i^{3}-3.62029*10^{5}*i^{4}+8.61806*10^{-8}*i^{5}-1.03234*10^{-10}*i^{6}+4.90737*10^{-14}*i^{7}$$. And Correlation coefficient of $R^2=1$ (4.5)

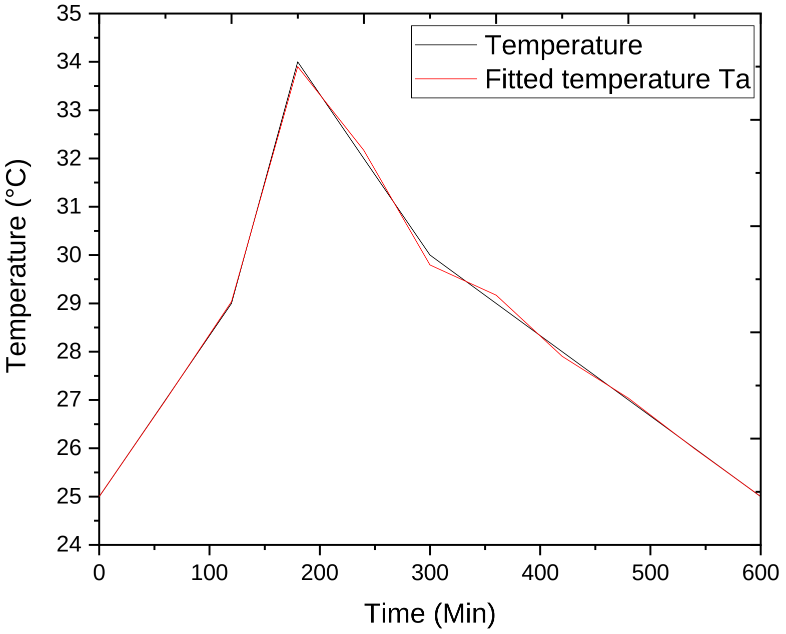

Figure 4.10 Variation in ambient temperature per min

Figure 4.10 shows the ambient temperature is being curve fitted as per equation

Input ambient temperature= $$Ta(i)=25+1.03006*i-0.04057*i^{2}+6.30736*10^{-4}*i^{3}-5.04693*10^{6}*i^{4}+2.33453*10^{-8}*i^{5}-6.51563*10^{-11}*i^{6}+1.08496*10^{-13}*i^{7}-9.93767*10^{17}*i^{8}+3.85563*10^{-20}*i^{9}.$$ (4.6)

The correlation coefficient of R^2= 0.99849

Where Ta (i) is ambient temperature per minute, i is nth min value.

An expression for water temperature and glass temperature obtained analytically using equation 4.5 and 4.6. with a time step of 60 seconds.

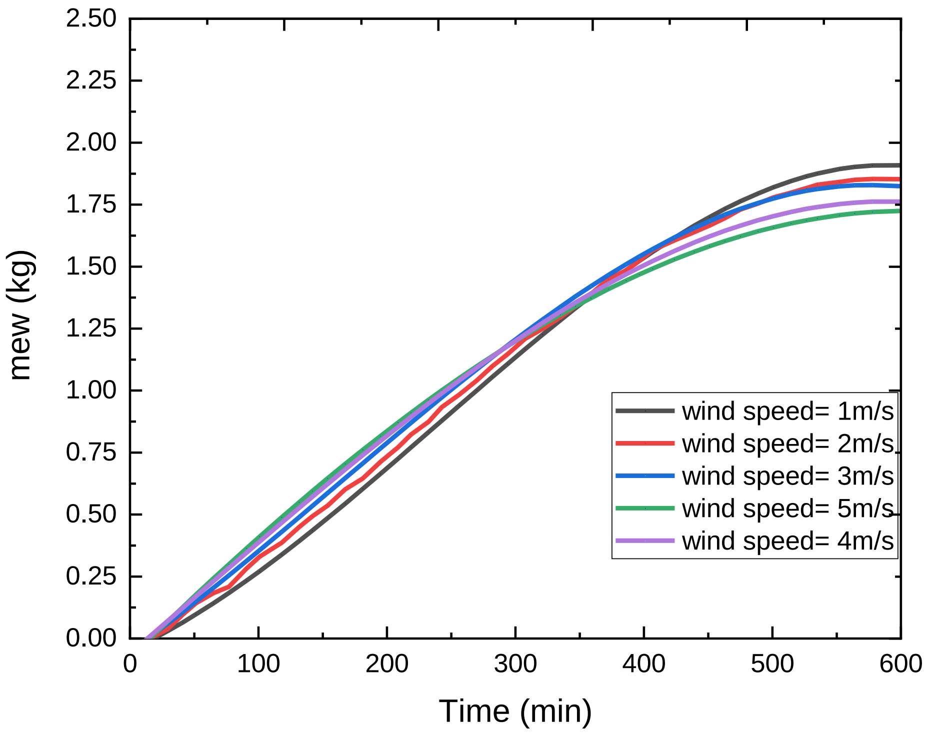

Figure 4.11 Effect of different wind speed for passive type solar still

Figure 4.11 shows the variation in still productivity for wind speed range 1-5 m/sec and it's been concluded from above results that higher wind speed that is 4, 5 m/sec dominates in first 300 min of a trail of an experiment after that when sunshine starts decreases it reverses the effect. The lower speed is effective in the later evening time. Reason of this reverse effect is that the water inside losses heat quickly resulting in low productivity.

With input solar irradiation the value of insolation starts decreasing after 230th min. then after 400min-600 min time period speed with value 1m/sec supports distillate output. Overall productivity reaches to 1.91 kg/day with 1 m/sec speed and error with high speed is 8.25% which is in the permissible limit.

Reason for low productivity is that the absorptivity of basin liner is taken as 0.5 which means low absorption of sun rays, which results in less heating of basin water, results in low evaporation rate. Productivity is half of that obtained in [44] for conventional still.

4.5 STUDY FOR COMPARISON BETWEEN CONVENTIONAL STILL AND STILL WITH PCM

Table 4.7 Thermophysical and design properties of conventional still

Lattitude and longitude of the place	Egypt (30.47°N,31°E)
wind speed (m/sec)	1.25
Cover angle (β_s)	30.47°
Area of basin (m^2)	0.72
The material used as bottom absorber	Galvanized iron sheet
Mass of material (kg)	8.4780
The thickness of bottom material (mm)	1.5
Area of glass cover(m^2)	0.8314
Mass of glass cover (kg)	6.25
Specific heat of glass (J/kg K)	0.8

Table 4.8 Paraffin wax properties [2]

Melting temperature (°C)	56
Thermal conductivity (W/m°C)	0.24
Liquid/solid heat capacity (kJ/kg°C)	2.51/2.95
Liquid/solid density (kg/m^3)	760/818
Latent heat (kJ/kg)	226

Table 4.9 Physical and operational properties of still with PCM [44]

Area of absorber plate used (m^2)	0.615
The thickness of absorber plate (mm)	0.4
The material of absorber plate	Copper
Specific heat of copper (J/kg K)	385
PCM	Paraffin wax
The thickness of PCM (cm)	3
Area of PCM (m^2)	0.72
Area of bottom PCM (m^2)	0.72
The material of bottom PCM reservoir	Galvanized iron sheet
The thickness of bottom (mm)	1.5

Assumptions

1. Still is assumed to be vapor leak proof.
2. There is no temperature gradient across the depth of water and PCM taken i.e temperature is assumed constant.
3. Wind speed is assumed to be constant at v=1.5m/sec.
4. The peak value of solar irradiance is at 1 pm noon.
5. Water depth is taken constant= 2cm.
6. There is no loss from bottom and sidewalls.

Input parameters for problem

1. Ambient temperature(Ta)
2. Solar insolation (I(t))

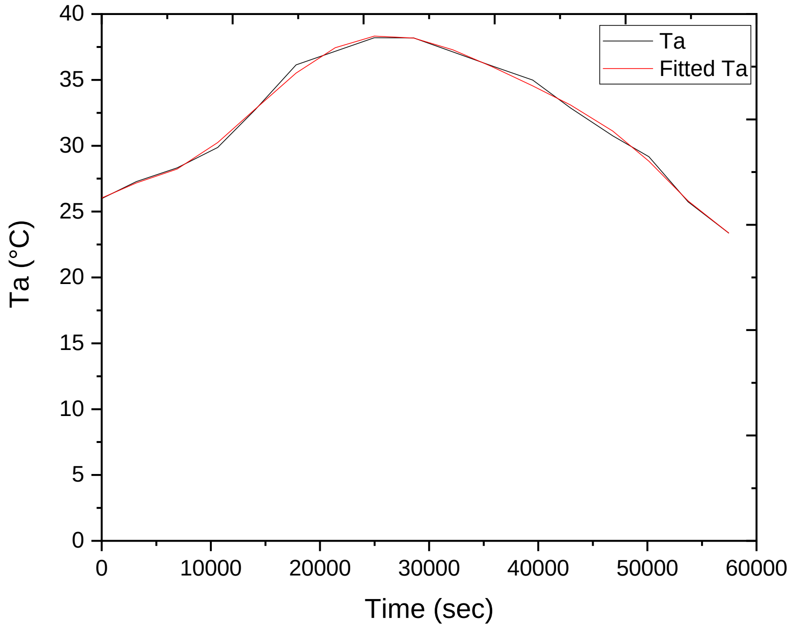

Figure 4.12 Ambient temperature variation

Using the values of the above parameters, the temperature of the glass cover and basin water temperature can be predicted. Other parameters like absorbtivity of glass, water, basin liner, the transmissivity of the glass cover, water are constant throughout the computation.

Figure 4.12 shows the ambient temperature of still per unit second for simulation and its curve fitted equation is as follows-

$$T(i)=26.03069+6.30574*10^{-4}*i-1.37432*10^{7}*i^{2}+1.96165*10^{-11}*i^{3}-1.08847*10^{-15}*i^{4}+2.844*10^{-20}*i^{5}-3.57541*10^{-25}*i^{6}+1.74711*10^{-30}*i^{7}. \quad (4.7)$$

Correlation coefficient of R^2=0.99445

This is an equation to input the ambient temperature values per second-time interval. Value of denotes the n^{th} value of the second.

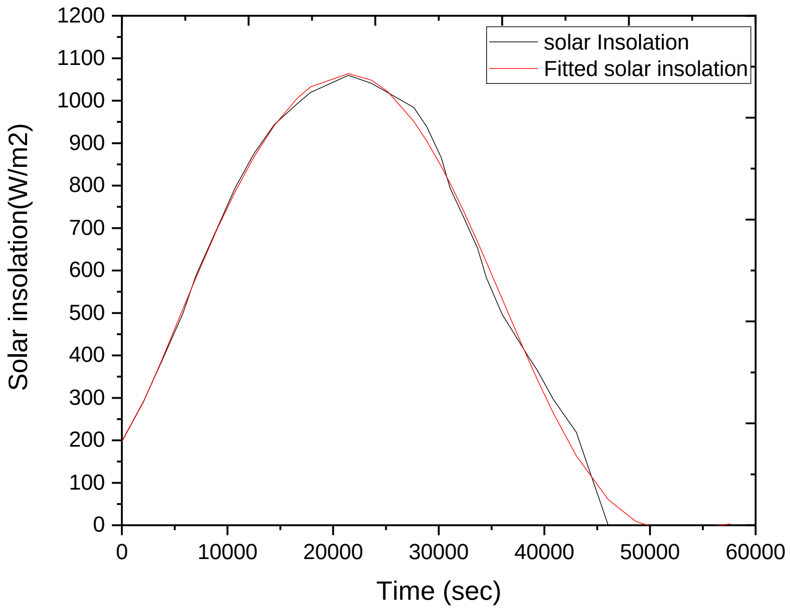

Figure 4.13 Solar irradiance variation for a time interval of 6 am to 10 pm

Input solar insolation is being curved fitted as shown in figure 4.13 and equation (4.8).

$$J(i)= 203.81427+0.03631*i+5.84942*10^{-6}*i^2-6.43047*10^{-10}*i^3+3.46603*10^{-14}*i^4$$

$$-1.21459*10^{-18}*i^5+2.47895*10^{-23}*i^6-2.5894*10^{-28}*i^7+1.0658*10^{-33}*i^8. \qquad (4.8)$$

The correlation coefficient of R^2=0.9962

Here 'i' represents the n^{th} value of second for we want the solar insolation. Above equation (4.8) is fitted value from experimental paper [44]. Input values at each second give the temperature value of basin water temperature, glass temperature, and these values help to predict the distillate produced at that particular second. Here time period is taken from 6 am to 10 pm night which is 57600sec.

Modified Euler's equation is used to solve the ordinary differential equations. This is also called the backward difference implicit method.

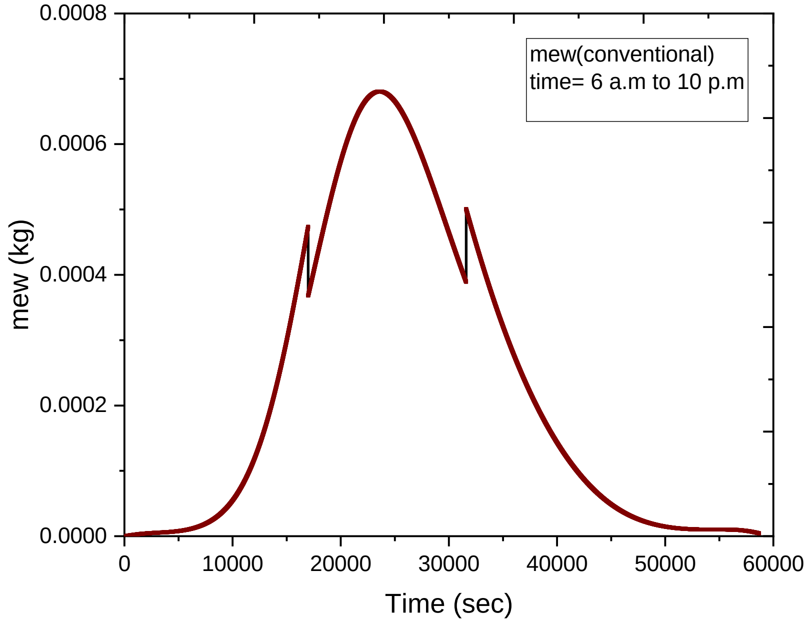

Figure 4.14 Distillate output for conventional still (6 am to 10 pm) at Egyptian conditions

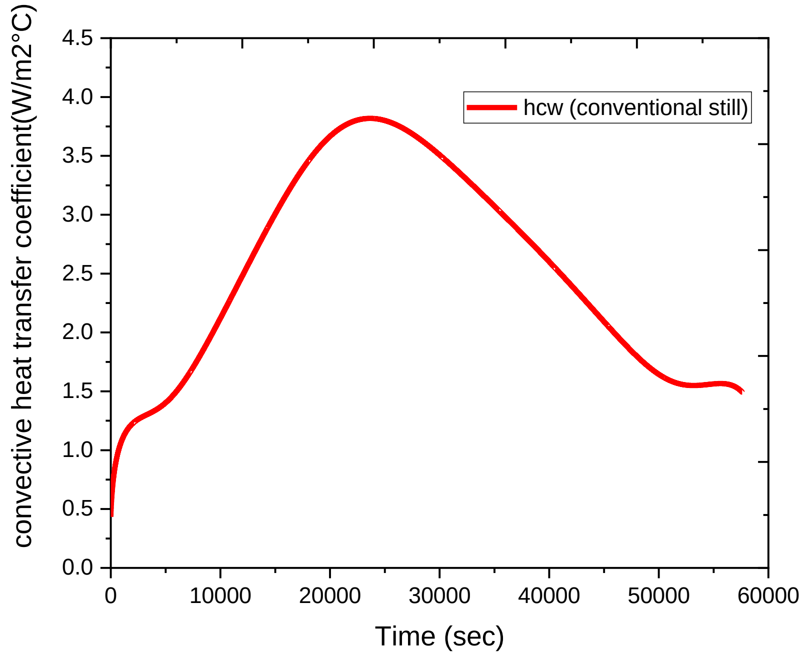

Figure 4.15 variation in convective heat transfer coefficient per sec for convention still

In figure 4.14, at i=1:57600 seconds, the mass of distillate produced by conventional still is 4.56 kg/m^2day. Maximum productivity is obtained between 12 pm to 3 pm. The productivity of conventional still drops suddenly after 5 pm. It's because of the unavailability of energy in the evening time.

In figure 4.15, for the time interval, 6 am to 10 pm curve obtained showed the maximum value is 3.81 (W/m^2°C) for the conventional solar still. Convective heat transfer coefficient lies between 0.45-3.81-1.84 (W/m^2°C) for a given time interval.

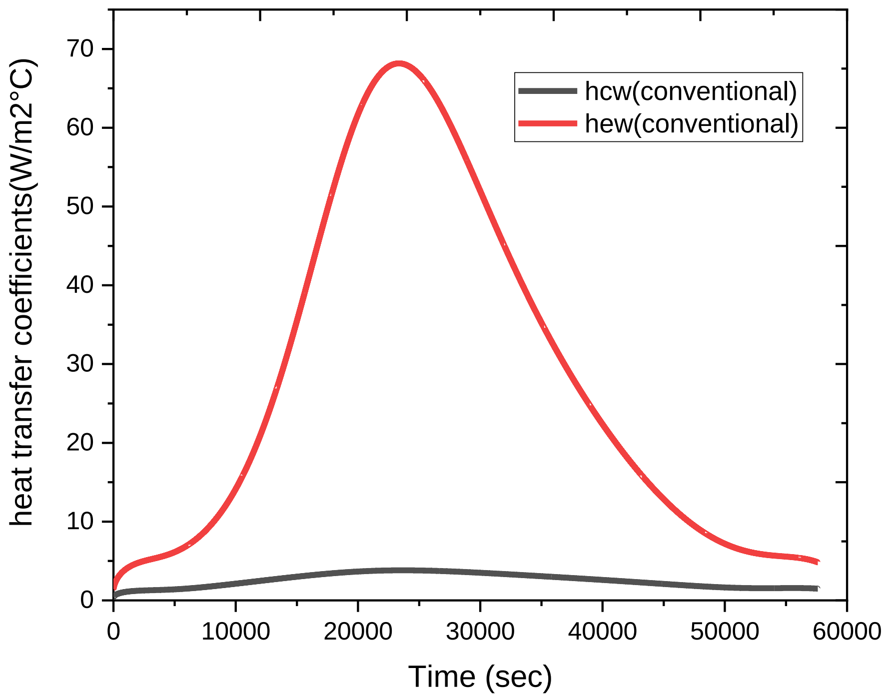

Figure 4.16 Comparison between heat transfer coefficients for conventional solar still

From researchers correlation given for convective and evaporative heat transfer coefficient its higher for evaporative. As figure 4.16 shows comparison justify it well. Value of evaporative heat transfer reaches to 68.11 (W/m^2°C) at time 23974th sec. Its value lies between 1.55-68.11-6.66 (W/m^2°C). At the starting of simulation, the value of convective and evaporative heat transfer increases linearly but after 2.5 hrs, the evaporative heat transfer coefficient increases quickly. Reason for this sudden rise is because of the increasing value of solar irradiance.

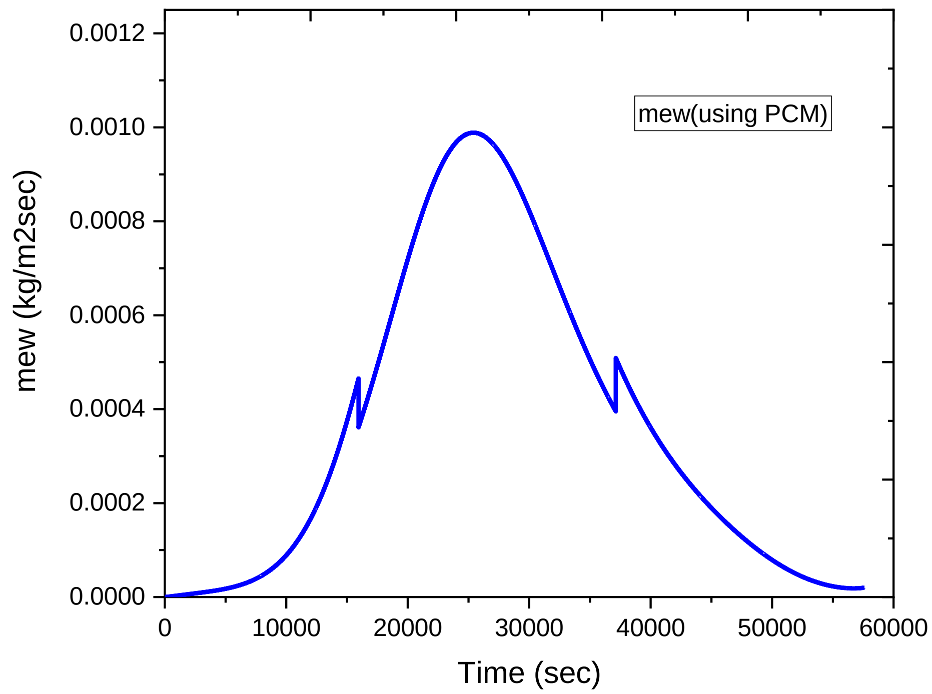

Figure 4.17 Variation of distillate output for solar still with PCM

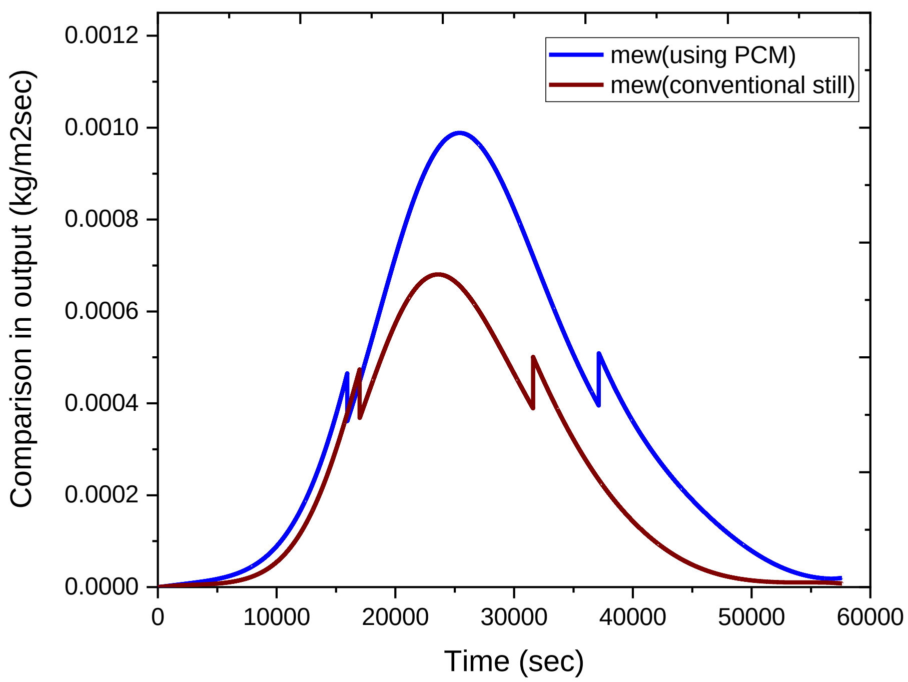

Figure 4.18 Comparison between distillate output (kg/m^2sec) for conventional and still with PCM

Figure 4.17 shows that maximum amount of distillate we get from 11-6 pm evening as compared to 11-3 pm for the conventional type of still. We got 82.5% increase in water productivity when we use paraffin wax with a thickness of 3cm. the accumulated value we got is 8.32 kg/m^{2}day as compared to 4.56 kg/m^{2}day using conventional still.

Also, there is a sudden drop in at two points in the graph which are at Tw= 70°C as latent heat of water is different for tw <=70°C and tw >70°C. as per relationship is given by previous researchers.

Solar still equipped with external thermal storage shows higher productivity than conventional stills. Figure 4.18 justify the same with the overall productivity of 8.32 kg/m^{2}day.

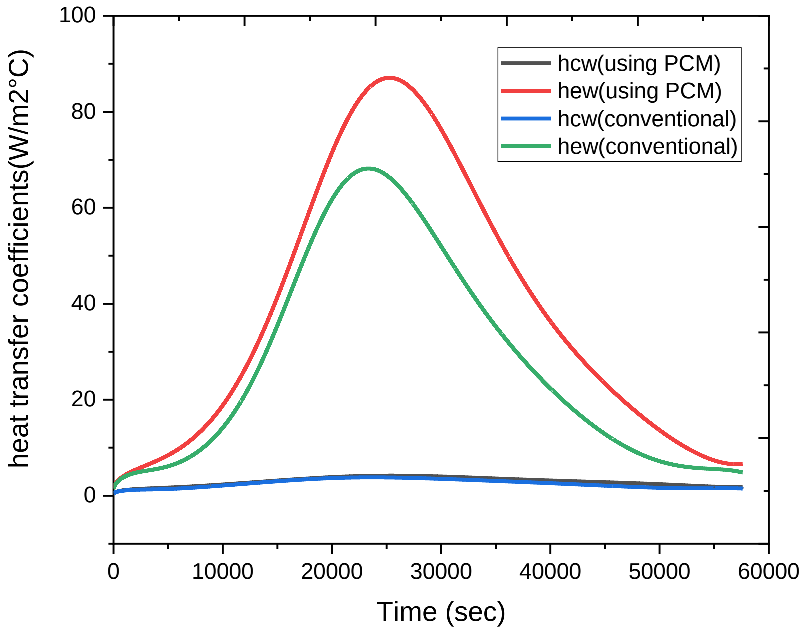

Figure 4.19 Comparison between convective and evaporative heat transfer coefficients for conventional and modified solar still with PCM

Comparison in Figure 4.19 for evaporative and convective heat transfer coefficient for conventional and modified still equipped with paraffin wax as heat storage material. The relation between convective and evaporative heat transfer is taken from Dunkle's empirical relation. Higher the value of evaporative heat transfer higher the distillate produced in solar still. The peak value of evaporative and convective heat transfer is around 12-1pm.

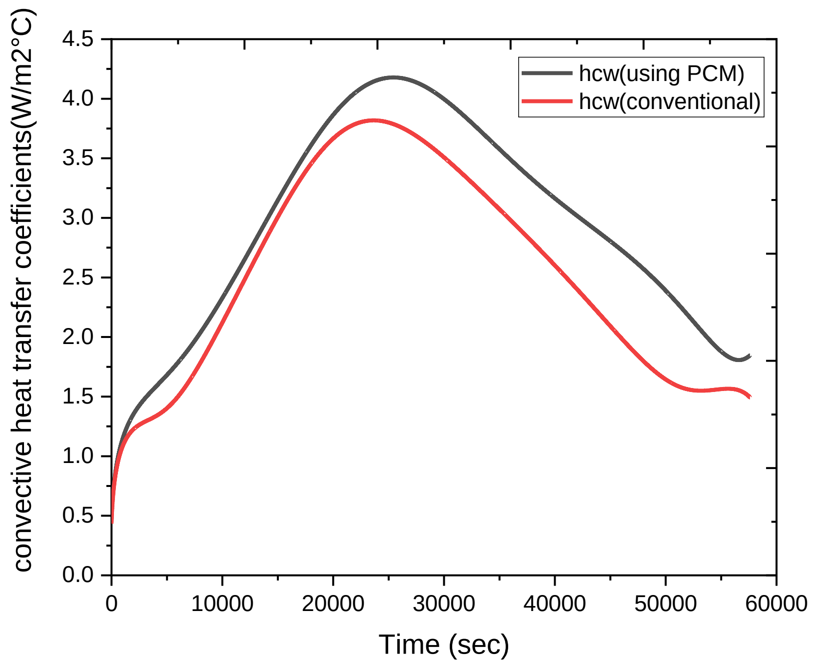

Figure 4.20 Comparison between convective heat transfer coefficients for conventional and modified still using PCM

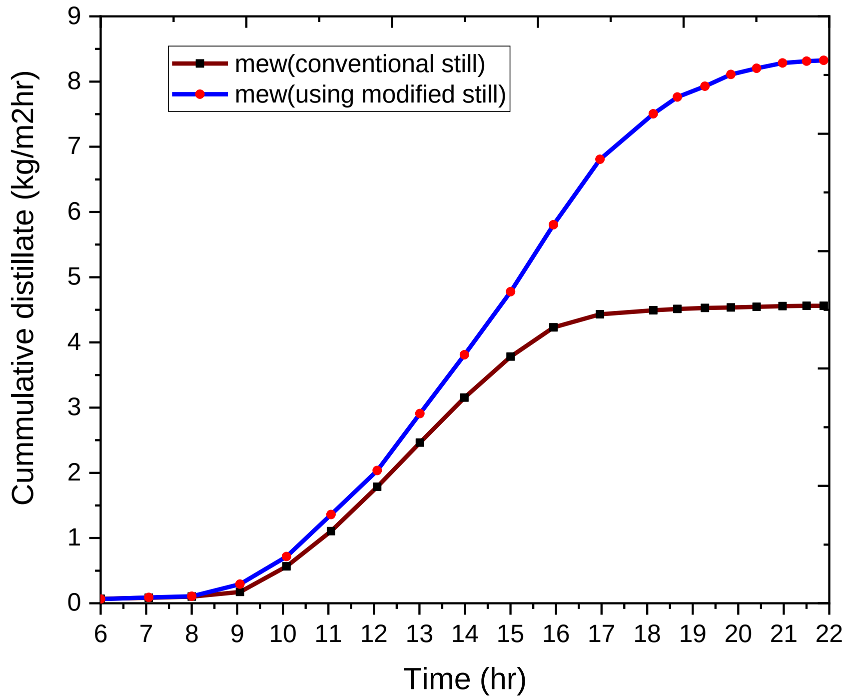

Figure 4.21 Accumulated water produced by solar still with and without PCM

The comparison in Figure 4.20 shows the internal heat transfer coefficients for solar still with and without PCM. Increase in heat transfer supports more distillate output. Dunkle model is used here to evaluate the convective heat transfer coefficient.

Figure 4.21 shows the productivity of both stills for a time period from 6.am to 10.pm. water collected through modified still was 8.3261 kg/m^2. While it was 4.56 kg/m^2 conventional still. The increase in water production was 82.51% when computed numerically while it was 67.18% when computed experimentally [44]. Reason for this change may be the losses in ambient conditions, assumed the uniform temperature of PCM throughout the thickness, variation in wind speed around the still. Solar insolation was taken in a range of 220-1080 W/m^2 [44]. Wind speed was taken 2m/sec according to data available on June 22-06-2015[1]. Maximum temperature attain was 84°C and for PCM (paraffin wax) it was 83°C. solar insolation attains peak value at 1 pm. Then it starts decreasing. Its becomes almost zero after 6 pm in the evening. Paraffin wax keeps basin water at higher temperature even in the evening time when solar energy is not available. Theoretical results show good agreement with experimental data. The error was within the range of 15%.

4.5.1 VALIDATION WITH EXPERIMENTAL RESULTS

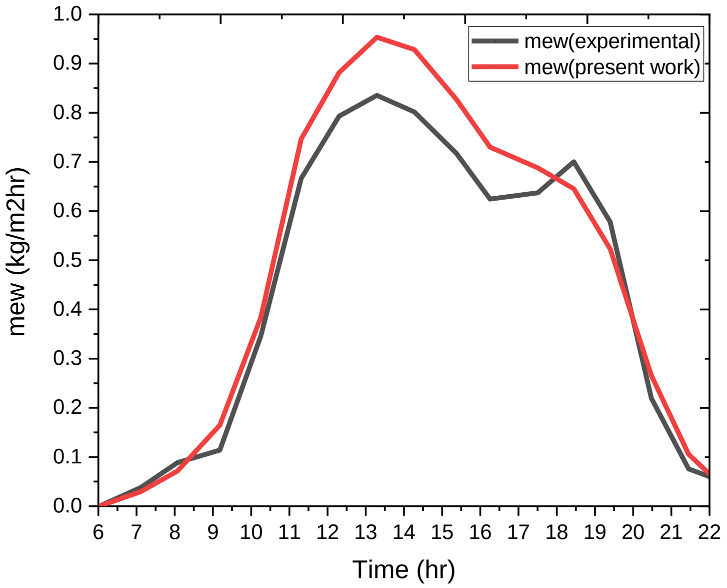

Figure 4.22 Comparison between present work and experimental [2] work in the same meteorological conditions for solar still using paraffin wax

Figure 4.22 showed a good relationship between theoretical and experimental work performed earlier. Results show that peak values are obtained nearby 12-3pm time interval and after that PCM keeps basin warm till evening. Theoretically, enhancement in the distillate is up to 83% using paraffin wax as heat storage.

4.5.2 EFFECT OF THICKNESS OF PCM ON DISTILLATE OUTPUT

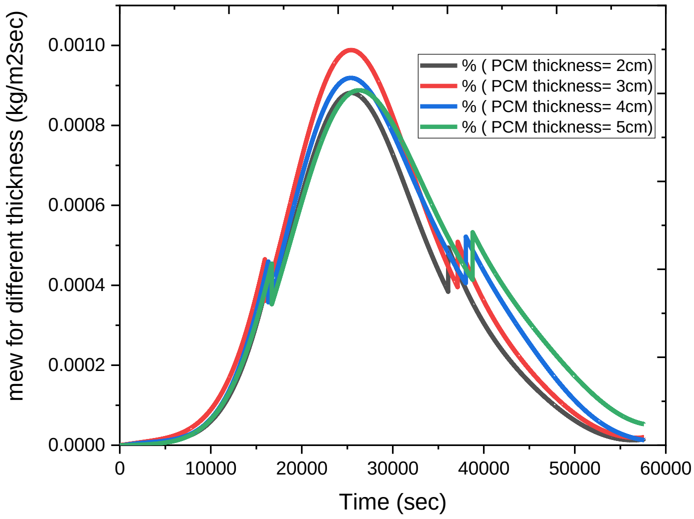

Figure 4.23 Distillate output per sec for different thickness of paraffin wax

Figure 4.23 shows that thickness of PCM held at 2cm, 3cm, 4cm and 5cm respectively. Results showed that there is not a significant change in output as compared cost increase with additional thickness [47]. Increase in efficiency was in the range of 5.89% in the case of paraffin wax. Increase in cost is up to 1300 INR per m^2 area for existing still.

In solar engineering storage of power in terms of thermal energy is limited to peak sunshine hours. In case of still equipped with PCM can store energy up to a maximum temperature of water i.e on peak sunshine hours after that, it starts releasing its energy and supply to basin water and keeps basin water hot in non-sunshine hours.

Table 4.10 Paraffin wax price estimation for different thickness

Paraffin wax	Mass(kg)	Cost(INR) Unit cost(78Rs/kg)
For a thickness of 2 cm	11.7792	918.7176
For a thickness of 3 cm	17.5	1365
For a thickness of 4 cm	23.4484	1837.60
For a thickness of 5 cm	29.448	2296.90

Table 4.10 describes the price of PCM for increasing thickness of paraffin wax. Increase in thickness has no significant effect on productivity but the price per unit cm is considerable. Paraffin wax is comparatively cheap in cost but other organic PCM are expensive in nature. The price difference is huge for increasing unit cm thickness. So it's recommended using optimum thickness which should justify the additional cost of Phase change materials.

4.5.3 EFFECT ON DISTILLATE PRODUCTION FOR DIFFERENT PCM USED

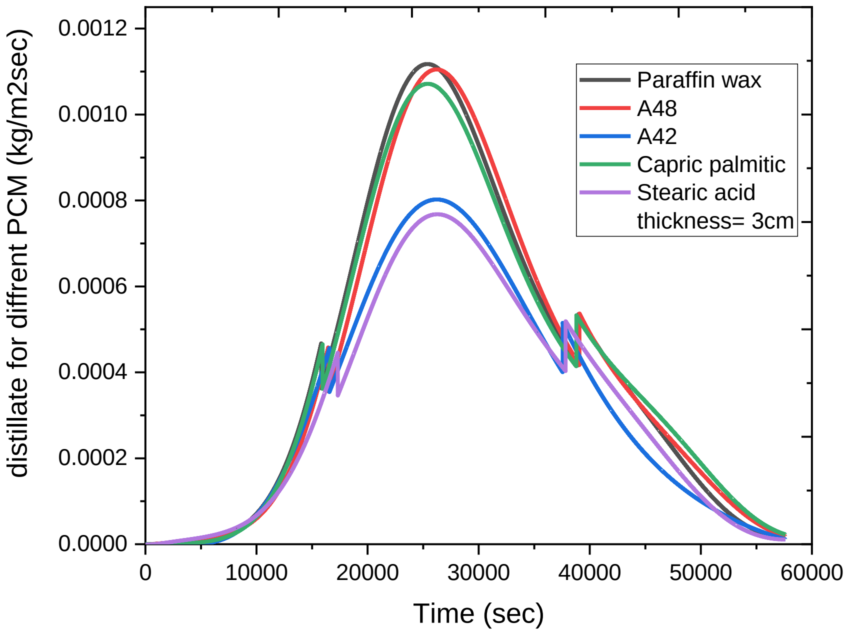

Figure 4.24 Distillate output per sec for different PCM at thickness=3cm

Figure 4.24 shows that there is an increase in productivity up to 91.75% in case of A-48 organic PCM used as compare to A-42 which showed increases in percentage to 84.55 %. Amount of distilled water production is (8.4155) kg/m^{2}day symbol A-48 represents melting temperature 48°C. Inorganic PCM Capric-palmitic gives an increase in productivity to 92% as compare to A-48. Also stearic acid shows 60% increment in efficiency as shown in table (4.11)

Table 4.11 Productivity and % increase for using different phase change material

Name of PCM	Productivity (kg/m^2day)	Percentage increase in efficiency (%)
Without PCM	4.56	---
Paraffin wax	8.32	82.55
A-48	8.74	91.75
A-42	8.41	84.55
Capric Palmitic	8.75	92
Stearic Acid	7.29	60

It’s noticed that Capric palmitic has a low melting point but its low value of conductivity and high sensible heat and latent heat provide high thermal storage. The cost is also an important parameter while making the selection of a PCM. Organic cost more than inorganic but has very less impact on the surroundings. The current simulation is done at a thickness of 3cm as the cost is also a parameter while designing a solar still.

CHAPTER -5

CONCLUSION AND FUTURE SCOPE

5.1 CONCLUSION

5.1.1 CONVENTIONAL SOLAR STILL

The passive type of solar still is cheap in cost and easy to operate solution to obtain fresh water for drinking and other purposes. The problem faced with a passive type of still is its thermal efficiency and productivity. Hence modification in still is a necessity. Addition of external thermal storage is one of the solutions to improve efficiency.

Depth of water also a strong operational parameter which affects the productivity strongly. With an increment in water depth from 5cm to 15 cm, it can cause loss peak hour productivity up to 72.35% as per present simulation. Losses are because of high specific heat of water, as it stores thermal energy sensibly which causes low evaporation and convection currents. Its recommended that water depth should be maintained between 2-5 cm for a general case to optimize the production of freshwater.

Slope angle or glass cover angle is an important design parameter which affects the productivity of a solar still. In general cases its matches with the latitude of that place where still has to operate. It's true for summer season but for winters it may vary. So it's advised that slope angle should be designed according to summers because at that time the requirement of water is more as compared to winter. In the present study for New Delhi (28.61°N, 77.20°E) simulation is done for a winter season. In the month of December, it's recommended using slope angle around 45° to get optimum output.

Wind effect is a meteorological parameter which slightly affects still productivity. With reference to kiam[1], a mathematical model was validated to given experimental data and it was concluded that higher wind speed increases the output to the first half of day where solar insolation is high in magnitude, After that its effect reverses. Overall lower wind speed gives the best results. In the present case, overall distillate collected was 1.90867kg/m^2day at speed 1 m/sec which is higher than 8.2545 % than with wind speed 5 m/sec.

Theoretical study purpose that with given cost and benefits it is strongly suggested that PCM should be attached to conventional still as it supplies thermal energy to basin water to keep it warm in non- sunshine hours. The freshwater productivity reaches to 8.32 kg/m^2day as compared to 4.56 kg/m^2day with conventional solar still.

5.1.2 SOLAR STILL WITH PCM

Paraffin wax is an organic type of PCM which is highly affordable with increased productivity up to 92%. In the present study in a given geography and meteorological conditions, paraffin wax increases productivity to 82.5% with a thickness of 3cm.

The thickness of the phase change material selected has no such significant effect on productivity. Paraffin wax with the thickness of 2-5 cm was simulated and it was observed that increase in efficiency within a range of 5.89% for a particular day in Egyptian conditions with increases in the cost of 1300 per m^2 for paraffin wax.

Comparing different PCM (A-48, A-42, Paraffin wax, stearic acid, capric palmitic) for same thickness for existing model gives a strong recommendation to use an organic PCM than Inorganic as organic PCM's has less impact on environment though they are little costly in nature. It was noticed to existing still with PCM A-48 and capric palmitic both are equally efficient as around 92% increase in efficiency but the cost per unit kg and per unit area is 5950 INR per unit area(m^2) is more for A-48 for same productivity. With A-42 increase in productivity was around 85% and stearic acid was least efficient with 60% increment in the present simulation.

5.2 FUTURE SCOPE

An attempt was made to increase the productivity of a single slope passive type of solar still to improve its efficiency. There are some future scope and work that can be done to improve the efficiency of still as-

1. The current model can be integrated with nono-fluids in basin water to improve productivity as nano-fluids increase basin water temperature and PCM supply heat in the absence of solar energy. So the attempt can be made with this type of model.
2. Cost of PCM is also an important parameter while a selection is made, a comparative study can, for a range of PCM available in the market.
3. Study of Seasonal variation with still equipped with PCM for the available number of sunny days of a place.
4. Connecting the existing model with a solar pond which supplies thermal energy to still externally.
5. Study with external condenser attached to the glass cover region to increase the condensation rate.

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