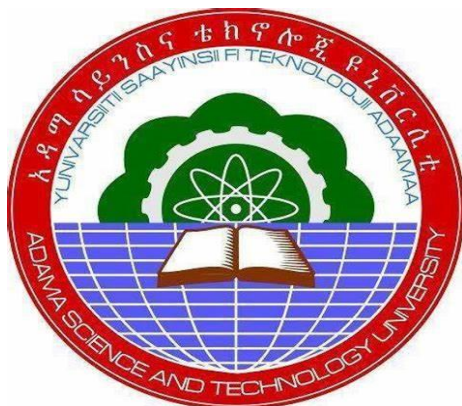


Investigating the Yield Improvement of Modified Passive Solar Still by using Nanoparticles



Adugna Dinkissa Abdissa

A Thesis Submitted to
The Department of Mechanical Engineering
School of Mechanical, Chemical and Materials Engineering
Presented in Partial Fulfillment of the Requirement for the Degree of
Master of Science in Thermal Engineering

Office of Graduate Studies
Adama Science and Technology University

June, 2022

Adama, Ethiopia

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DECLARATION

First, I hereby declare that this Master of Science Thesis entitled “*Investigating the Yield Improvement of Modified Passive Solar Still by using Nanoparticles*” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled *“Investigating the Yield Improvement of Modified Passive Solar Still by using Nanoparticles”* prepared under my guidance by Adugna Dinkissa Abdissa submitted in partial fulfillment of the requirements for the degree of Master of Science in Thermal Engineering. Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

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I, the advisor of the thesis entitled hereby “*Investigating the Yield Improvement of Modified Passive Solar Still by using Nanoparticles*” and developed by Adugna Dinkissa Abdissa, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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ACKNOWLEDGEMENT

My utmost gratitude is to God Almighty, the Creator and the Sustainer of the heavens and the earth and all that exists in between. Secondly, I take this opportunity to place on record my profound sense of recognition and deep appreciation to my advisor, Dr. Addisu Bekele for his personnel encouragement, valuable suggestions, unending benevolence, stimulating discussions and able guidance right from the beginning to date as a result of which the present study reached fruition. My gratitude to him knows no bounds.

Next, I express my sincere thanks to my instructors Dr. Dawit Gudeta and Dr. Gezahegn Habtamu for their invaluable encouragement, constructive suggestions, inspiration throughout my academic life, and support from an early stage of this thesis and for providing me extraordinary experiences through the work. Then, I would like to thank all my well-wishers, colleagues and friends to make this thesis more valuable and aids an appreciated contributions for my research work.

A special gratitude goes to my beloved parents for their encouragement, support, love and affection which keeps me going always. I would like to show my deepest gratitude to people who made my time fruitful at Adama Science and Technology University (ASTU) which I will remember and treasure for long. Last but not the least, I am also grateful to ASTU for their provision in providing me all necessary support.

TABLE OF CONTENTS

CONTENTS	PAGE
ACKNOWLEDGEMENT.....	v
TABLE OF CONTENTS	vi
LIST OF TABLES	x
LIST OF FIGURES	xi
LIST OF SYMBOLS AND NOMENCLATURES.....	xiv
ABSTRACT.....	xvi
CHAPTER ONE	1
INTRODUCTION.....	1
1.1 Background of the Study	1
1.2 Working Principle of Solar Still	2
1.3 Statement of Problem.....	2
1.4 Objectives of the Study.....	3
1.4.1 General Objective	3
1.4.2 Specific Objective	3
1.5 Scope and Limitations of the Study	3
1.6 Significance of the Study	4
1.7 Outline of the Study	4
CHAPTER TWO	5
LITERATURE REVIEW	5
2.1 Solar Energy	5
2.2 Solar Still	5
2.3 Classification of Solar Stills	6
2.4 Passive Solar Stills.....	7
2.4.1 Basin Solar Stills.....	7
2.4.2 New Designed Solar Stills	9
2.4.3 Inclined Solar Stills.....	15
2.5 Parameters Affecting the Yield of Solar Stills.....	16
2.5.1 Climatic Parameters	16
2.5.2 Design Parameters	17

2.5.3 Operational Parameters	19
2.6 Nanoparticles (NPs)	20
2.7 Thermal Energy Storage	22
2.7.1 Selection of PCM	23
2.8 Nano-embodied Phase Change Materials (NPCMs)	23
2.9 Energy, Exergy and Economic Analysis	24
2.10 Design Improvements and Modifications of Passive Solar Stills	26
2.10.1 Design Amendments in Passive Solar Stills	28
2.11 Enhancement Methodology	31
2.12 Water Quality Analysis	31
2.13 Proposed Solar Desalination Techniques Identified from Literature Review	32
2.14 Summary of Literature Survey	33
2.15 Research Gap and Outcomes of Literature Survey	33
CHAPTER THREE	35
MATERIALS AND METHOD	35
3.1 Method	35
3.1.1 Literature Review	37
3.1.2 Data Collection	37
3.1.3 Physical Concept	37
3.1.4 Mathematical Model	37
3.1.5 Validation	38
3.2 Water Sampling	38
CHAPTER FOUR	39
DESIGN AND THEORETICAL ANALYSIS OF SOLAR STILLS	39
4.1 Analysis and Estimation of Solar Radiation Intensity	39
4.1.1 Data Collected from Meteorology	39
4.1.2 Sunshine Hour Duration and Wind Speed	40
4.2 Extraterrestrial Daily Solar Radiation on a Horizontal Surface	42
4.2.1 Estimation of Hourly Solar Radiation on a Horizontal Surfaces	43
4.2.2 Estimation of Total Incident Solar Radiation on a Tilted Surface	47
4.3 Fantale Metrological Temperature Data	48

4.3.1 Estimation of Hourly Variation of Ambient Temperature.....	49
4.4 Material Selection of the Solar Still Components	50
4.5 Daily Requirements of Drinking Water.....	52
4.6 Design of a Solar Still.....	54
4.6.1 Design Details of a Conventional Pyramid Solar Still (CPSS).....	54
4.6.2 Design Details of a Modified Pyramid Solar Still (MPSS)	58
4.7 Conceptual Model and Design Specification of Solar Still Materials	65
4.8 Parameter Description of a Solar Still	66
4.9 Mechanisms of Heat and Mass Transfer Modes in a Solar Still.....	67
4.9.1 Internal Heat Transmission	68
4.9.2 External Heat Transmission	71
4.10 Energy Analysis.....	73
4.10.1 Energy Balance of Solar Still Components.....	74
4.11 Exergy Analysis.....	80
4.11.1 Fundamental Concept of Exergy and Exergy Efficiency of Solar Still	81
4.11.2 Exergy Destruction of Solar Still Components.....	82
4.12 Numerical Solution and Procedure	86
4.12.1 Methodology for Solving the Equations	86
CHAPTER FIVE	88
EXPERIMENTAL SETUP AND PROCEDURE	88
5.1 Fabrication Process	88
5.1.1 Fabrication of the Basin Storage.....	88
5.2 Preparation of Copper Oxide Nanofluids	88
5.3 Experimental Set-up	89
5.3.1 Conventional Pyramid Solar Still	89
5.3.2 Modified Pyramid Solar Still	90
5.4 Location of the Test	93
5.5 Experimental Procedure.....	94
5.6 Description of the Instruments.....	94
5.7 Experimental Analysis and Experimentation	95
5.7.1 Experiments Conducted	95

5.8 Experimental Uncertainty Analysis	96
CHAPTER SIX	97
RESULTS AND DISCUSSIONS	97
6.1 Variations in the Intensity of the Solar Radiation with Time	97
6.2 Ambient Temperature Profile	98
6.3 Experimental Observations of Pyramid Solar Still.....	98
6.3.1 Varying the Levels of the Water	98
6.3.2 Effects of Proposed Modifications.....	111
6.4 Theoretical Analysis of MPSS under Fantale’s Climatic Condition	116
6.5 Energy Efficiency	118
6.6 Exergy Efficiency	119
6.7 Comparison of the CPSS and MPSS	119
6.8 Comparison of Present Study with Previous Research Work.....	120
6.9 Water Quality Analysis.....	121
CHAPTER SEVEN.....	122
CONCLUSIONS AND RECOMMENDATIONS.....	122
7.1 Conclusions.....	122
7.2 Recommendations.....	123
REFERENCES.....	124
APPENDIXES	134
Appendix-A: X-ray Diffractometer (XRD) Result	134
Appendix-B: Analytical Analysis of Nanofluid	134
Appendix-C: Experimental Observation with Various Depth of Water	138
Appendix-D: Thermocouple Calibration	139
Appendix-E: Description of Measuring Instruments used and their Accuracy	140
Appendix-F: Figures Taken during Water Quality Test.....	141
Appendix-G: Economic Analysis	143
Appendix-H: MATLAB Program Code	146
Appendix-I: Drawing of Solar Still Parts	149

LIST OF TABLES

TABLES	PAGE
Table 2.1: Summary of the literature review in table	34
Table 4.1: Estimation of monthly average daily sunshine hour and wind speed of Fantale.....	40
Table 4.2: Monthly average temperature annual climatic conditions of Fantale.....	48
Table 4.3: Summary of the materials components of the solar still considered	51
Table 4.4: Nanoparticle size of copper oxide	60
Table 4.5: Thermophysical properties of CuO nanoparticles	61
Table 4.6: The value of volume concentration that used on the experiment	61
Table 4.7: Thermophysical properties of paraffin wax and CuO nanoparticles	62
Table 4.8: Design specifications and technical details of the solar stills.....	66
Table 4.9: The main specifications reference for solar still used in analyses.....	66
Table 4.10: Various heat transfer modes inside and outside the solar still.....	68
Table 5.1: Specifications of the measuring instrument with parameter.....	94
Table 6.1: Average values of yield, thermal and exergy efficiency of CPSS and MPSS.....	120
Table 6.2: Comparison of the present work with earlier research works	120
Table 6.3: Water quality analysis of saline and distilled water	121
Table C-1: Experimental observation of the CPSS at 1 cm water level.....	138
Table C-2: Experimental observation of the CPSS at 2 cm water level.....	138
Table D-3: Water temperature measuring test by using k-type thermocouples.....	139
Table E-4: Accuracy and error for various measuring instruments.....	141
Table F-5: Methods and instruments used to find the physio-chemical properties of water.....	141
Table G-6: Equipment and initial investment cost of the proposed solar still.....	143
Table G-7: Economic analysis of the conventional and modified pyramid solar stills	145

LIST OF FIGURES

FIGURES	PAGE
Figure 1.1: Schematic diagram of conventional solar still	2
Figure 2.1: Classification of solar still.....	6
Figure 2.2: The schematic of a conventional single-slope single-basin passive solar still.....	8
Figure 2.3: Schematic sketch of regenerative solar still	8
Figure 2.4: Schematic view of the both double slope solar stills	9
Figure 2.5: Schematic view of pyramid-shaped solar still.....	10
Figure 2.6: Schematic diagram of concave wick solar still	10
Figure 2.7: Schematic view of hemispherical solar still	11
Figure 2.8: Schematic view of spherical solar still	12
Figure 2.9: Schematic view of triangular solar still.....	13
Figure 2.10: Schematic view of tubular solar still	13
Figure 2.11: Solar distiller with capillary film condenser	14
Figure 2.12: Schematic view of cascade solar still.....	15
Figure 2.13: Schematic view of inclined solar still	15
Figure 2.14: Parameters affecting the basin type of solar still productivity	16
Figure 2.15: Design amendments in passive solar stills	31
Figure 3.1: Flow-chart for the methodological approach and progressive steps	36
Figure 3.2: Samples of saline water poured from Lake Basaka	38
Figure 4.1: Monthly averagely sunshine duration for each month of Fantale	40
Figure 4.2: Monthly average daily extraterrestrial radiation on a horizontal surface.....	43
Figure 4.3: Monthly average daily global radiation on a horizontal surface	44
Figure 4.4: Monthly average daily global, diffuse and beam radiation on a horizontal surface .	45
Figure 4.5: Monthly average hourly global solar radiation on a horizontal surface.....	46
Figure 4.6: Monthly average hourly total incident solar radiation on a tilted surface.....	48
Figure 4.7: Monthly average maximum and minimum temperatures of Fantale	49
Figure 4.8: Result of average variations of ambient temperature of Fantale.....	50
Figure 4.9: A schematic view of square pyramidal shape	53
Figure 4.10: A schematic view of conventional pyramid solar still	55
Figure 4.11: Water storage basin (a) 3D Model (b) Top view (c) Front view.....	55

Figure 4.12: Outer box storage basin (a) 3D Model (b) Top view (c) Front view	56
Figure 4.13: Square pyramidal shape (a) 3D Model (b) Top view (c) Front view	57
Figure 4.14: A Schematic diagram of modified pyramid solar still	58
Figure 4.15: V-corrugated absorber basin (a) 3D Model (b) Front view (c) Top view	58
Figure 4.16: Pictorial view of pyramid solar still	65
Figure 4.17: Heat transfer processes within a pyramid solar still.....	68
Figure 4.18: Schematic illustration of energy balance for solar still	73
Figure 4.19: Thermal resistance network for solar still	74
Figure 4.20: Heat Energy balance of a glass cover.....	75
Figure 4.21: Energy balance diagram of brackish water in basin.....	76
Figure 4.22: Energy balance diagram of absorber plate	77
Figure 4.23: Energy balance diagram of PCM	78
Figure 4.24: Energy balance diagram of absorber plate without PCM	79
Figure 4.25: Exergy balance of a glass cover	82
Figure 4.26: Exergy balance of a saline water	84
Figure 4.27: Exergy balance of an absorber plate with PCM.....	84
Figure 4.28: Exergy balance of an absorber plate without PCM.....	85
Figure 4.29: Flow-chart for theoretical analysis of a solar still	87
Figure 5.1: Manufacturing process of the basin solar still for CPSS and MPSS.....	88
Figure 5.2: Steps and equipment's incorporate in nanofluids preparation	89
Figure 5.3: Experimental setup of the conventional pyramid solar still.....	90
Figure 5.4: Copper oxide nanoparticles and black paint procured from market	91
Figure 5.5: PCM filling process.....	92
Figure 5.6: Experimental setup of the modified pyramid solar still	93
Figure 5.7: Pictorial view of experimental setup with necessary instrumentations.....	95
Figure 6.1: Estimated solar radiation of Adama's climatic condition in May month	97
Figure 6.2: Variation of ambient temperature with solar time in May month.....	98
Figure 6.3: Variations of ambient temperatures observed during experimentation	99
Figure 6.4: Hourly variations of absorber plate temperature with CPSS	100
Figure 6.5: Hourly variations of absorber plate temperature with MPSS	100
Figure 6.6: Variations of water temperatures with CPSS	101

Figure 6.7: Hourly variations of water temperatures with MPSS.....	102
Figure 6.8: Variations of glass cover temperatures with CPSS.....	103
Figure 6.9: Hourly variations of glass cover temperatures with MPSS.....	103
Figure 6.10: Hourly variations of evaporation heat transfer coefficients of CPSS	104
Figure 6.11: Hourly variations of evaporation heat transfer coefficients of MPSS	105
Figure 6.12: Hourly variations of PCM temperatures with MPSS	106
Figure 6.13: Charging and discharge time of PCM at 1 cm water depth	108
Figure 6.14: Charging and discharge time of PCM at 2 cm water depth	109
Figure 6.15: Charging and discharge time of PCM at 3 water depth	109
Figure 6.16: Comparison of the cumulative yield for CPSS	110
Figure 6.17: Comparison of the cumulative yield for MPSS	111
Figure 6.18: Hourly variations of temperatures with v-corrugated absorber surface.....	112
Figure 6.19: Hourly variations of temperatures of with nano-coating surface.....	113
Figure 6.20: Variations of temperatures versus solar time with internal reflectors.....	114
Figure 6.21: Hourly variations of temperatures versus solar time with NPCM	114
Figure 6.22: Cumulative yield and effects of proposed modifications.....	115
Figure 6.23: Hourly variations of absorber plate temperature with MPSS	116
Figure 6.24: Hourly variations of water temperature with MPSS	116
Figure 6.25: Hourly variations of glass temperature with MPSS.....	117
Figure 6.26: Comparison of the cumulative yield for CPSS	117
Figure 6.27: Thermal daily efficiency of CPSS and MPSS.....	118
Figure 6.28: Average exergy efficiency of a solar still with CPSS and MPSS	119
Figure A-1: XRD pattern of CuO nanoparticle	134
Figure B-2: Relation of volume concentration and weight of nanoparticle	135
Figure B-3: Relation of volume concentration and thermal conductivity of nanofluid.....	136
Figure B-4: Volume concentration of nanoparticles versus specific heat capacity	136
Figure B-5: Volume concentration of nanoparticles versus density	137
Figure B-6: Relation of volume concentration and viscosity of nanofluid.....	137
Figure D-7: Calibration setup with standard and k-type thermocouples	139
Figure D-8: Measured Temperature versus Corrected temperature	140
Figure F-9: Figures taken during water quality analysis	143

LIST OF SYMBOLS AND NOMENCLATURES

ACRONYMS

Symbols	Description	Symbols	Description
AC	Annual Cost	NP	Nanoparticle
AMC	Annual Maintenance Cost	NPCM	Nano Phase Change Material
ASV	Annual Salvage Value	PCM	Phase Change Material
CPL	Cost of Production per Liter	pH	Potential of Hydrogen
CRF	Capital Recovery Factor	PP	Payback Period
CPSS	Conventional Pyramid Solar Still	SFF	Sinking Fund Factor
CSS	Conventional Solar Still	SS	Solar Still
EC	Electrical Conductivity	SSSS	Single Slope Solar Still
FAC	First Annual Cost	TAC	Total Annual Cost
FC	Fixed Cost	TDS	Total Dissolved Solid
MPSS	Modified Pyramid Solar Still	TSS	Total Suspended Solids
MSS	Modified Solar Still	WHO	World Health Organization

NOMENCLATURES

Symbols	Description	Units [IS]
A	Area	m^2
C_p	Specific heat	J/kg °C
d_w	Water depth in basin	m
E	Energy	J
Ex	Exergy rate	W
H	Monthly average daily global solar radiation on horizontal surface	J/m ² /day
h	Heat transfer coefficient	W/m ² °C
H_o	Monthly average daily extraterrestrial solar radiation on a horizontal	J/m ² /day
h_{fg}	Latent heat of vaporization of water	J/kg
I	Monthly average hourly global solar radiation on horizontal surface	W/m ²
$I(t)$	Intensity of solar radiation	W/m ²
I_o	Extraterrestrial solar radiation on a horizontal surface	W/m ²
I_T	Total hourly irradiance on a tilted surface	W/m ²

K	Thermal conductivity	W/m °C
m	Mass	kg
n_s	Monthly average daily hours of bright sunshine	-
p	Partial saturated vapor pressure	N/m ²
Q	Convective heat transfer	W/m ²
t	Thickness	m
T	Temperature	°C
U_t	Overall top heat transfer coefficient from basin water to ambient	W/m ² °C
V	Wind speed	m/s

GREEK SYMBOLS

Symbols	Description	Units	Symbols	Description	Units
α	Absorptivity	-	η	Efficiency of solar still	%
α_s	Solar altitude angle	(°)	θ	Angle of incidence	(°)
β	Tilt angle	(°)	θ_z	Zenith angle	(°)
γ	Surface azimuth angle	(°)	ρ	Density	Kg/m ³
γ_s	Solar azimuth angle	(°)	ϕ	Latitude	(°)
δ	Declination	(°)	ω	Solar hour angle	(°)
ε	Emissivity	-	τ	Transmittance	-

SUBSCRIPTS AND SUPERSCRIPTS

Symbols	Description	Symbols	Description
a	Ambient	$loss$	Loss
b	Beam	nf	Nanofluid
c	Convection	p	Absorber plate
d	Diffuse	r	Radiation
des	Destruction	sky	Sky
e	Evaporation	sr	Sunrise
ex	Exergy	ss	Sunset
g	Glass cover	sun	Sun
ins	Insulation	w	Basin water

ABSTRACT

Passive solar still continues to become a more feasible and cost-effective option for the desalination of saline water in remote villages. However, the reported efficiency of conventional solar still was in the range of 30 - 45% and its yield was less than 5 L/m² per day. A significant amount of heat energy is lost through the basin and sidewalls of solar still to the atmosphere, which is the foremost reason behind its underperformance. This is the major drawbacks of passive solar still that need improvement. The analyzes were carried out with two distinct pyramid solar still: one is a modified pyramid solar still with a unique combination of impactful modifications such as v-corrugated absorber, nano-coated absorber surface, nano-embodied phase change material and internal reflective mirrors, and the other is a conventional pyramid solar still that serves as the reference case. The methodology followed to achieve this study was based on the objectives formulated. This study was conducted by reviewing the scientific literature and then performing a theoretical analysis under the solar radiation of Fantale climatic conditions. Due to the difficulties of the transportation of setup, the process of the experimentation was carried out under Adama's climatic conditions. The components of the solar still was designed based on the daily requirements of drinking water of an average rural family and constructed from locally available materials. The influence of several parameters like effect of water depth, impact of proposed modifications and effect of concentrations of nanoparticle on the proposed solar still was studied. A thermodynamic model based on the first and second law of thermodynamics was conducted to predict the energy and exergy performance of the system. The yield of freshwater obtained from conventional and modified pyramid solar still was 2.95 and 5.73 L/m² day, respectively, with improvement of 94.2%. The average thermal efficiency of the conventional and modified pyramid solar still were 43.9 and 63.72%, respectively, with enhancement of 45.1%. The average exergy efficiency of the conventional and modified pyramid solar still were 2.2 and 3.7%, respectively, with enrichment of 68.2%. Finally, the water quality test has been done for saline and distilled water, shows good agreement with world health organization limit.

Keywords: Solar distillation, Passive solar still, Saline water, Nano-coated, Evaporation

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Ethiopia is one of the African countries rich in ground and surface water that is used for a different purpose. However, some of these water bodies are polluted naturally due to their saline property like Lake Basaka and others polluted by human activities. Lake Basaka has a maximum amount of saline water (EC~3.17 mS, pH~9.73) and poor water quality that could not be used for drinking and irrigation purposes. This Lake has created several problems instead of giving an advantage to the community. Desalinating this saline water and pollutant removal may reduce water scarcity and will show the possible use of Lake Basaka for villages nearby. Desalination is a process for eliminating salt content from saline water (Mu *et al.*, 2021).

Solar stills are recognized as one of the most appropriate desalination techniques uses solar energy that aim to make saline water drinkable with simple thermodynamic processes. They are simple, inexpensive, and easy to maintain, making them a promising option for remote areas (Abdelgaied *et al.*, 2022; Mohsenzadeh *et al.*, 2021). A single basin single slope solar still is the most basic type of solar still. This technology uses a closed device called solar still in which water is evaporated using solar energy, which collects distilled water after condensation of the vapor and left impurities on base (Darbari and Rashidi, 2022). However, the drawback of this technology is low efficiency and productivity (Jobrane *et al.*, 2022; Younes *et al.*, 2022). A significant amount of heat energy is lost through the basin and sidewalls of solar still to the atmosphere, which is the foremost reason behind its underperformance.

To solve this issue, many studies have been conducted and until now they continue to improve the yield, efficiency, and effectiveness of solar stills. The yield enhancement of solar still could be obtained by proper design modifications. Therefore, the present study attempted to overcome the research gaps by investigating the yield augmentation of passive solar stills incorporated with nanoparticles and suitable design modifications. This study examines the usage of passive solar stills. Performance parameters like yield of freshwater, thermal efficiency, heat transfer, energy, and exergy efficiency have been investigated under Fantale climatic conditions. The obtained results compared with similar solar stills that have been reported in the aforementioned literature.

1.2 Working Principle of Solar Still

The working principle of solar still is the same as the hydrological cycle found in nature. For distillation, the saline water is poured into the basin. The solar radiation falling over the transparent glass cover gets a pass through it and strikes the inner surface of the basin. The inner surface of the basin is blackened so that it absorbs most of the radiation. The saline water in the basin gets heated up and begins to evaporate. Vapors start to rise to leave behind the salt and impurities. When the vapor reaches the inclined glass cover it gets condensed on the inner glass surface and the condensed water runs down due to gravity in the collecting channel. Finally, the condensed water is taken out of the system and is collected for direct use. The simple schematic diagram of single slope solar still is shown in Figure 1.1 (Le *et al.*, 2021).

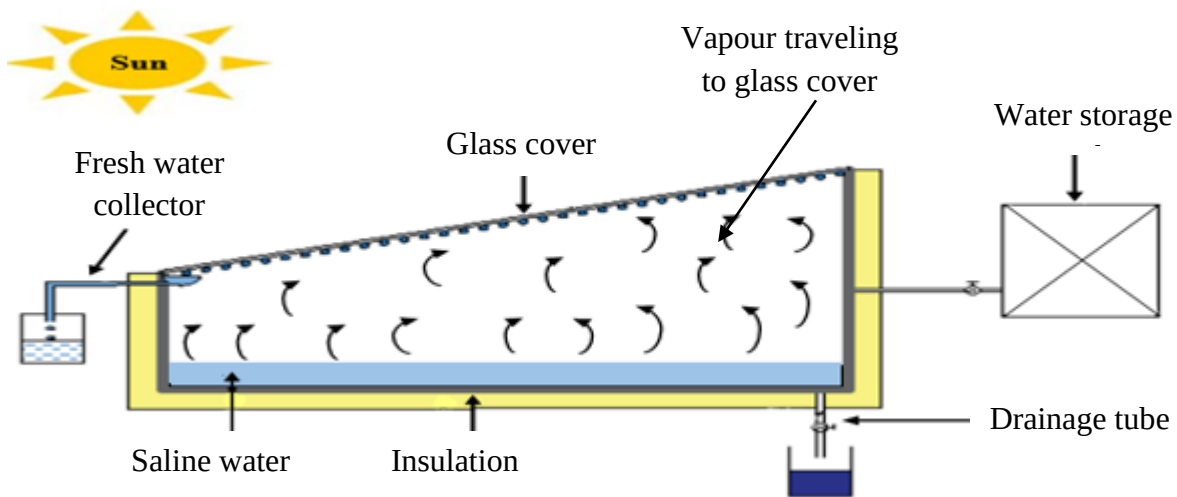


Figure 1.1: Schematic diagram of conventional solar still

1.3 Statement of Problem

Passive solar stills are becoming more feasible in village areas and cost-effective for desalinating saline water. The reported efficiency of conventional solar still was in the range of 30-45% and yield was less than 5 L/m² per day (Narayanan *et al.*, 2020). Many studies have been attempted to overcome the low efficiency of solar still by making various types of design modifications. However, low efficiency and yield of freshwater are major drawbacks that need improvement. A significant amount of heat energy is lost through the basin and sidewalls of solar still to the atmosphere, which is the leading cause behind its underperformance, which reduces the yield and energy efficiency of solar still. This study has focused on the freshwater yield improvement of passive solar still by using nanoparticles and suitable design modifications.

1.4 Objectives of the Study

1.4.1 General Objective

The general objective of this study is to investigate the yield improvement of modified passive solar still by using nanoparticles for an average family in villages.

1.4.2 Specific Objective

The specific objectives of this present study are

- To examine the saline property and its composition of Lake Basaka water
- To design and manufacture the conventional solar still
- To perform various design modifications on the conventional solar still
- To perform numerical investigation for the modified solar still and identify best parameters to provide the maximum yield of freshwater
- To develop a prototype of the best solar still based on the numerical investigation
- To perform an experimental investigation for the conventional and modified solar still
- To analyze the effect of various concentrations of nanoparticles on the yield of freshwater
- To compare the best parameters for the maximum freshwater yield of the conventional and modified solar still

1.5 Scope and Limitations of the Study

The scope of this study is an investigating the yield improvement of modified passive solar still by using nanoparticles for the distillation of saline water, which is poured from Lake Basaka. In this study, the proposed solar still uses energy from the sun for the distillation process to produce potable water on a small scale. Its yield in terms of distillate output and energy efficiency is analyzed under Adama climatic conditions. The rate of drinking water produced per day using the proposed solar still has been examined. The proposed solar still was fabricated with locally available low-cost materials and experimentally tested. The experiment was conducted to examine the influence of several parameters on the proposed solar still yield. The intermittent availability of solar radiation affects the performance of this system. The potential availability of solar radiation at Fantale is more suitable for solar desalination process. However, due to the difficulties of the transportation of setup to that place, the process of the experiments was conducted at Adama climatic conditions. Finally, the water quality test has been done for saline and distilled water.

1.6 Significance of the Study

The significance of this study shows the possible use of Lake Basaka for drinking purposes and family needs for villages nearby. This study was relevant to human health, environmentally friendly cleanliness, free energy, response to the growing demand for freshwater, and fabrication using locally available materials. This study enables the use of solar still and serves as a foothold, especially in the area of solar desalination research in Ethiopia.

1.7 Outline of the Study

A brief introduction on the contents of the thesis report was outlined as follows. Literature review of solar desalination system was briefed in chapter two. Chapter three focuses on the materials and methods implemented to achieve the objectives. Chapter four discusses the design and theoretical analysis of solar still in detail. The development process of the experimental setup and its analysis was explained in chapter five. Chapter six comprises the various results and their discussions. Finally, chapter seven discuss the conclusions and recommendations for future work.

CHAPTER TWO

LITERATURE REVIEW

This chapter provides a variety of literature reviews relevant to the different designs of solar stills utilized at a domestic level. The solar still is well known among scientists for its simple operating principle and easy generation of the distillate output water. Many researchers have put forth a lot of effort to improve its output. Several studies were performed to improve the daily productivity, thermal efficiency, and economic effectiveness of passive solar stills (SSs).

2.1 Solar Energy

The utilization of renewable energy, such as wind, solar, and geothermal energy, has been emerging as a promising solution for decreasing the dependence on fossil fuels for desalination. Significant effort is being made to use renewable energy for desalination, particularly in a remote areas and isolated islands where sufficient electric power infrastructure is lacking. While renewable energy's contribution to meeting global energy demand is growing, it is still insignificant (Mu *et al.*, 2021). Solar energy is usually the first choice among these renewable alternatives because of its accessibility. Comprehensive reviews of solar energy utilization in water desalination was reported by (Le *et al.*, 2021). Solar radiation is abundant in many underdeveloped countries that could not otherwise afford desalinated water. Ethiopia receives 4 to 7 kWh/m² of annual mean average solar irradiation and with an average of 250 to 300 clear sunny days per year according to region and season (Agonafer, 2020). The annual mean average solar radiation is more or less uniform, around 5.2 kWh/m², with an average sunlight length of more than 10 hours per day throughout the year and thus has great potential for the use of solar energy. Solar desalination can be a reasonable choice to utilize the solar energy in a cost-effective way.

2.2 Solar Still

Solar still is a device which works on the principle of solar distillation and provides potable water. Commercial water desalination systems are not viable to implement in remote places due to the scarcity of electricity and fossil fuels in those areas. Thus, solar still continues to be the most efficient alternative to providing clean water to remote villages. As the name implies, solar still uses the heat energy of sunlight to distill water. Solar energy is inexhaustible, abundant, and clean. These features make it the best alternative of all renewable energy sources. The typical solar still works on the principle of evaporation and condensation phenomena.

2.3 Classification of Solar Stills

The broad category of solar still can be summarized by (Narayanan *et al.*, 2020; Singh *et al.*, 2020; Muftah *et al.*, 2014). Solar stills can be categorized into passive and active distillation systems. Passive solar stills are those in which the saline water once fed to the still basin and receives the energy from the sun itself. No additional thermal energy collector from an external source is supplied to the saline water in the still basin. Whereas in active solar still, water is firstly heated in the solar collector or from the waste thermal energy of industries and then it is fed to the solar still. Active solar stills use thermal collectors from an external source, photovoltaic panels, and concentrators can be connected with a basin of solar still. This extra thermal energy elevates the evaporation rate further. Solar stills can be further categorized as shown in Figure 2.1, depending on how solar energy is harnessed stated by (Manchanda and Kumar, 2015).

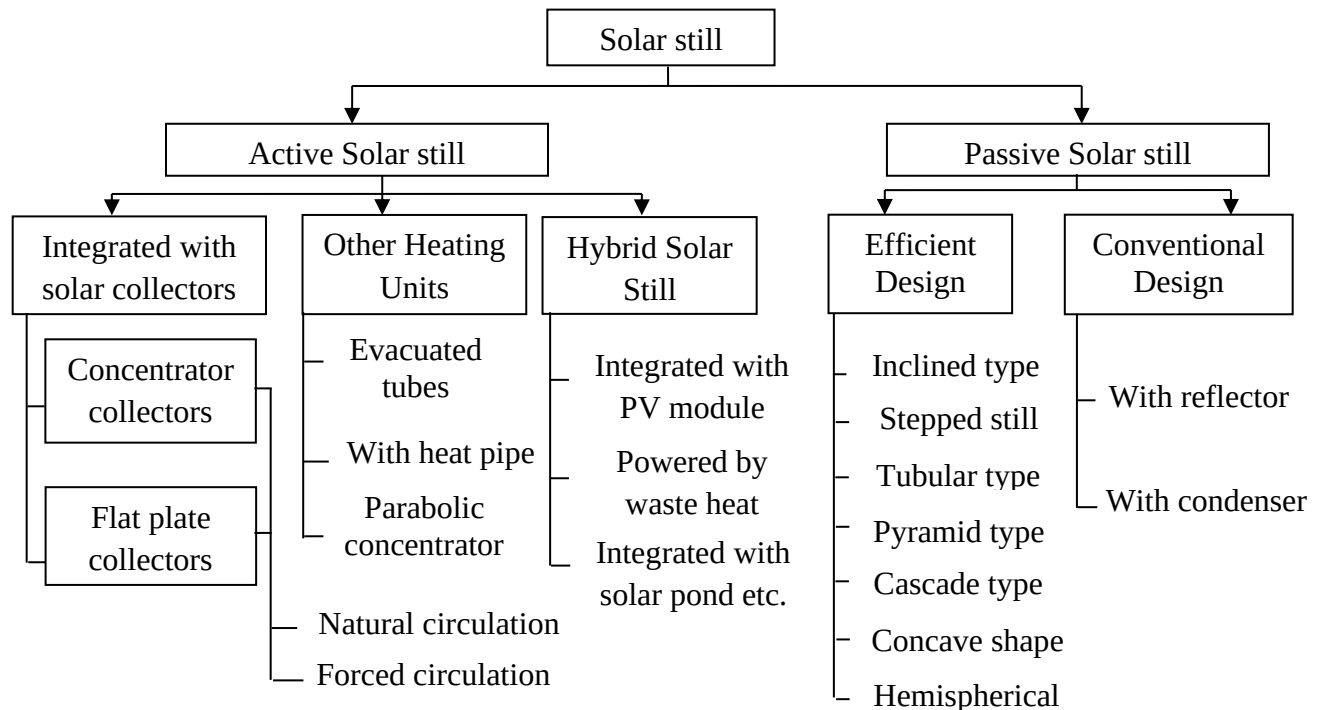


Figure 2.1: Classification of solar still

The main difference between passive and active solar stills is that evaporation and condensation occur without the use of moving parts in a passive solar still. On the other hand, active solar still, uses electricity to increase its yield by utilizing additional devices like as fans, pumps, and external condensers to aid its thermal operations (Mu *et al.*, 2021). Active solar stills have a complex structure and usually need electricity to operate. Therefore, considering the lack of access to the

electric power infrastructure and the maintenance professionals in many remote areas, passive type of solar stills would be a feasible option to address the water security challenge in villages or remote areas. Passive solar stills are less expensive, have a simpler structure, and are simple to operate, making them a better option for isolated places with greater annual solar radiation averages (Mohsenzadeh *et al.*, 2021). Several studies have been performed to improve the productivity of solar still, and several review articles have been published in this area.

2.4 Passive Solar Stills

Passive solar still is the simplest design for distilling saline water by harnessing solar energy. In a passive solar still, evaporation and condensation processes take place naturally. Passive solar stills are classified into three types as follows: basin solar still, new designed solar still, and inclined solar still.

2.4.1 Basin Solar Stills

This is the most conventional and basic type of solar still which contains a layer of raw saline water to be desalinated. To cover the entire setup, a transparent cover of glass or plastic sheet is used at the top. The saline water in the basin evaporates, as the basin water temperature increases due to sun's radiation and the generated water vapor condense on the inner surface of the glass cover. The distillate output of the solar distiller varies with various atmospheric conditions and design parameters.

2.4.1.1 Single Slope Single Basin Solar Still

Single slope solar still (SSSS) consists of a basin and a transparent cover. In basin still, impure water is taken in a well-insulated air tight basin which is covered with transparent cover. When solar radiation falls on the cover, the solar energy is transmitted inside the basin and evaporates the basin fluid. The evaporated fluid gets condensed and drained using collecting troughs. The efficiency of the distiller is increased by increasing the temperature of the basin water at the inlet and the intensity of solar radiation. A schematic simple basin still is shown in Figure 2.2 (Mohsenzadeh *et al.*, 2021).

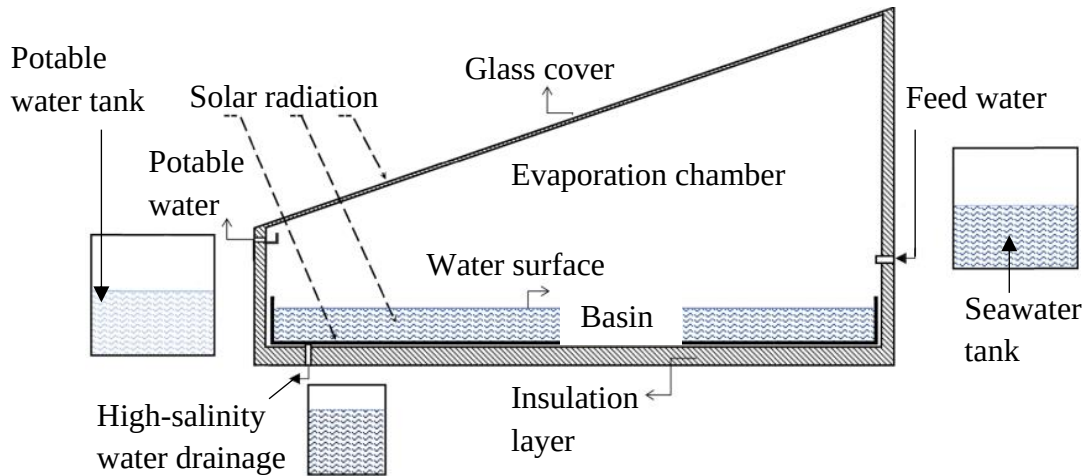


Figure 2.2: The schematic of a conventional single-slope single-basin passive solar still

2.4.1.2 Regenerative Solar Still with Double Glass

In a regenerative still with double glass, the lower glass acts a second basin which cools the vapour from first basin and regenerate heat to the second basin water as shown in Figure 2.3 (Zurigat and Abu, 2004). In the first effect, it raises the temperature differential between the water and the glass cover. This produces more potable water in the second effect. Regenerative still gave 20% higher yield than the conventional solar still (Velmurugan and Srithar, 2011).

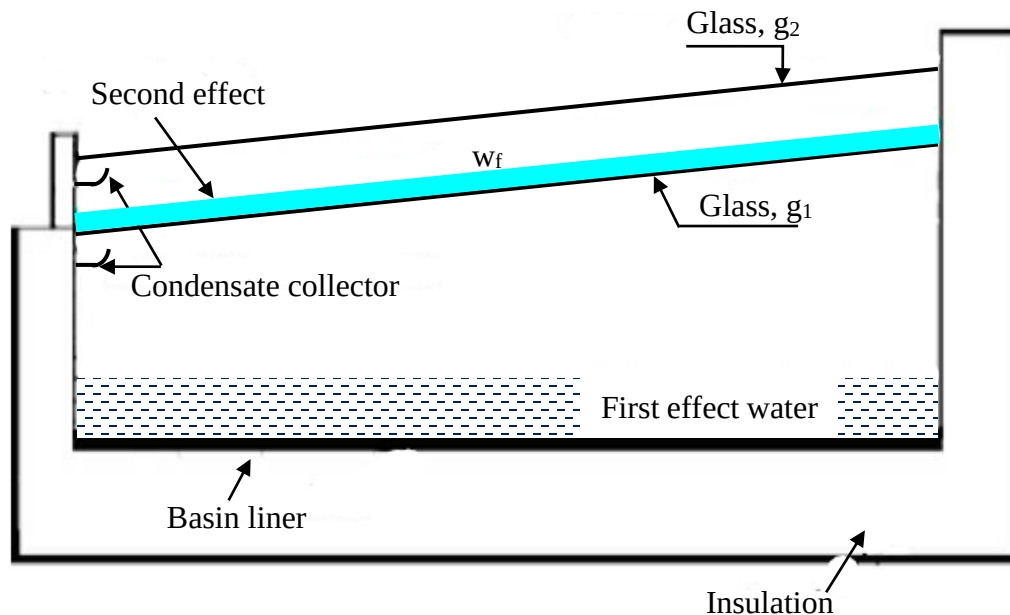


Figure 2.3: Schematic sketch of regenerative solar still

Generally, basin solar still is the simplest type of stills which is easy to fabricate, however, it has some downsides like more heat loss. For instance, due to its particular geometry, the glass cover

absorbs less radiation which results in lower yield, compared to double slope solar stills. While, the structure of the basin solar still has been modified by researchers during last decades to improve the yield.

2.4.2 New Designed Solar Stills

The solar still efficiency is heavily influenced by design variation. To improve distillate productivity, some researchers have manufactured and experimentally tested certain efficient and innovative designs of solar stills. In terms of heat storage, parametric variation, heat loss coefficient, and orientation, a few investigations were conducted on a newly constructed solar still. Solar stills come in a variety of designs. Here are a few of them:

2.4.2.1 Double Slope Solar Still (DSSS)

DSSS works similar to that of single slope solar still but it contains two glass covers that increase the condensation area. Rajaseenivasan and Murugavel, (2013) conducted a study on the yield, performance, and dependent parameters of a double basin solar still at Tamil Nadu, India. In comparison to the single basin system, they deduced that providing an additional basin increased the yield by 85 and reached 2.99 L/day. Despite the fact that the lower basin's productivity was higher, an increase in water mass in both the upper and lower basins lowered the rate of output. The schematic view of DSSS shown in Figure 2.4 (Rajaseenivasan and Murugavel, 2013).

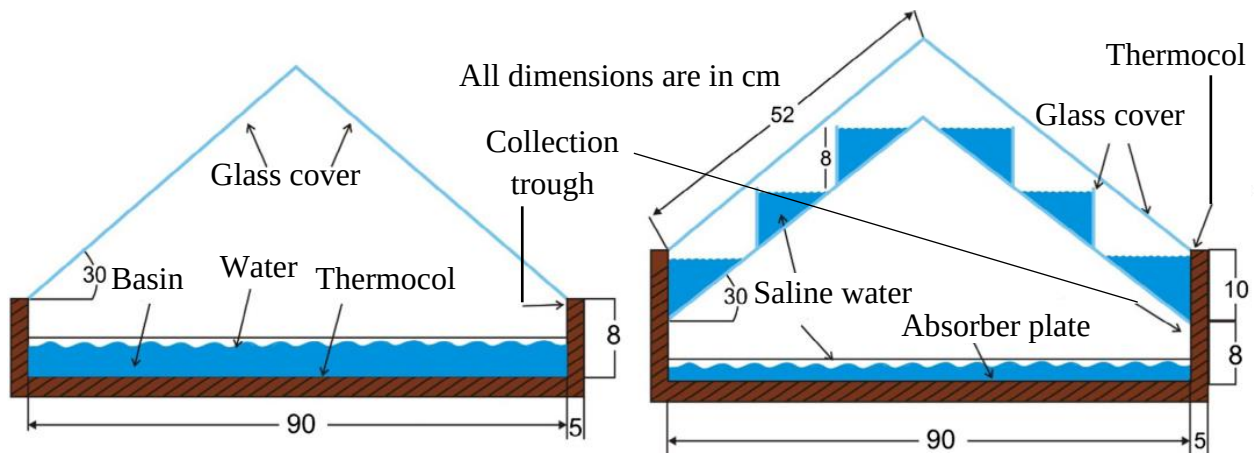


Figure 2.4: Schematic view of the both double slope solar stills

The fundamental conclusions of double slope solar still is that appropriate water depth must be maintained and that the solar still must be asymmetric with optimal orientation in order to achieve high production.

2.4.2.2 Pyramidal Solar Still

A new design of solar still with a pyramid shape top cover for water desalination was pretend by (Arunkumar *et al.*, 2012). The outer basin of the still was made of mild steel with a square aperture of $1.1 \times 1.1 \text{ m}^2$. Saw dust was used to insulate the sides and bottom of the basin. The still was filled with a saline water to height of 0.05 m. They reported that the distilled yield of water was 3.3 L/m^2 day. The schematic view of the pyramid solar still is shown in Figure 2.5 (Arunkumar *et al.*, 2012).

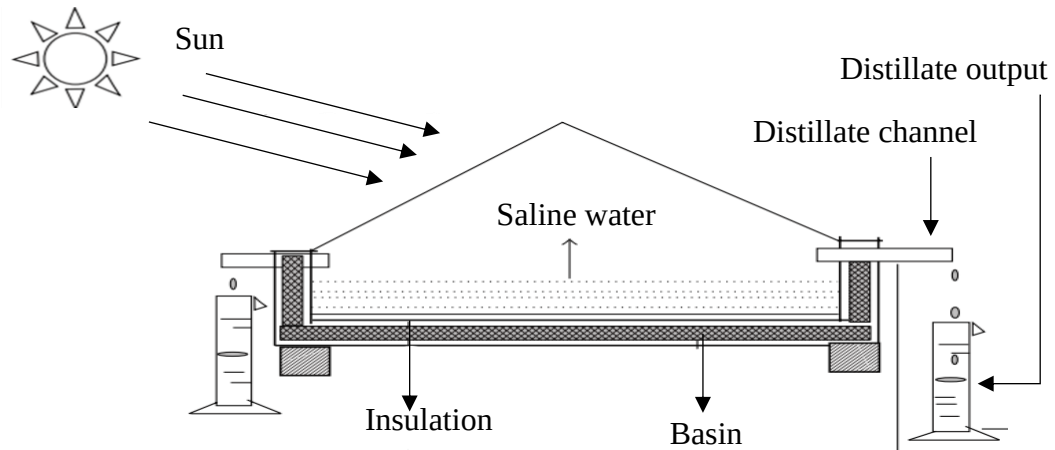


Figure 2.5: Schematic view of pyramid-shaped solar still

2.4.2.3 Concave Wick Solar Still

A four sides of a pyramid shaped cover were framed with concave wick surface was fabricated by (Kabeel, 2009). The schematic diagram of concave wick solar still is shown in Figure 2.6.

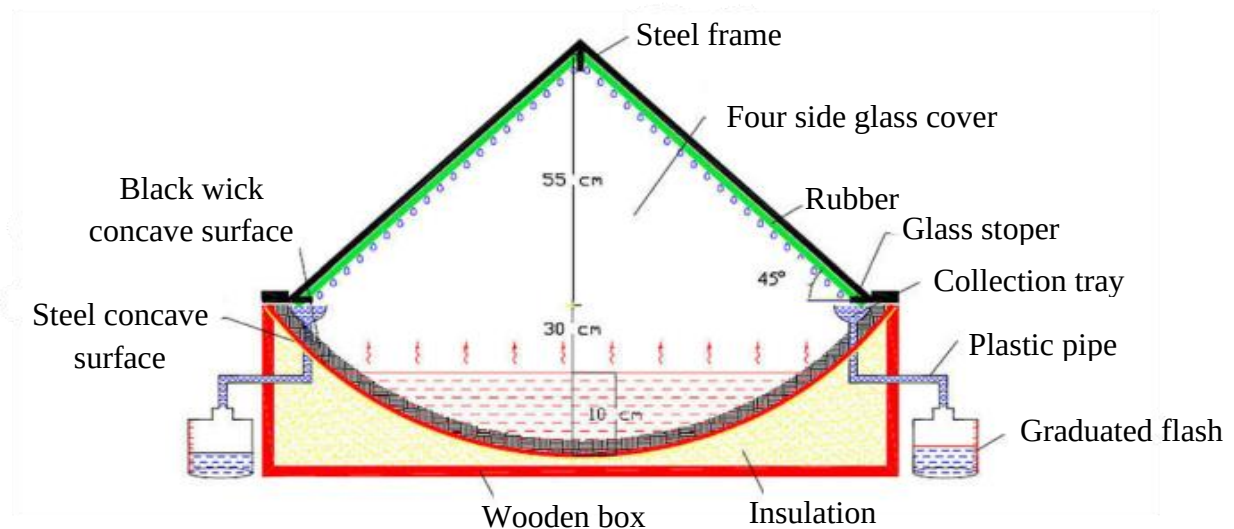


Figure 2.6: Schematic diagram of concave wick solar still

The author showed that the average daily freshwater yield and efficiency was 4.1 L/m² day and 45%, respectively. The maximum hourly yield was 0.5 L/h m² after solar noon. An estimated cost of 1 L of distillate was 0.065 \$ for the existing solar still.

Generally, pyramid solar still and concave shaped wick surface can be used to absorb more solar radiation due to their geometrical shape from various directions than single slope solar still. This increases the evaporation area and pyramid shaped cover used for condensation. However, when we compare their efficiency with a standard conventional solar still, pyramid solar still gives better efficiency.

2.4.2.4 Hemispherical Solar Still

A new design of solar still with a hemispherical top cover for water distillation (with and without flowing water over the cover) was invented by (Jayaprakash *et al.*, 2012). The outer box of the still was made of 4 mm thickness wood with dimension of 1.1 x 1.1 x 0.25 m. HSS made up of transparent acrylic sheet of 3 mm thickness. Saw dust was filled up to a height of 0.15 m. Glass wool was used to insulate the sides of the basin. They found that the distilled yield of water without cooling and with cooling was 3.66 and 4.2 L/m² day, respectively. The schematic sketch of the hemispherical solar still is shown in Figure 2.7 (Jayaprakash *et al.*, 2012).

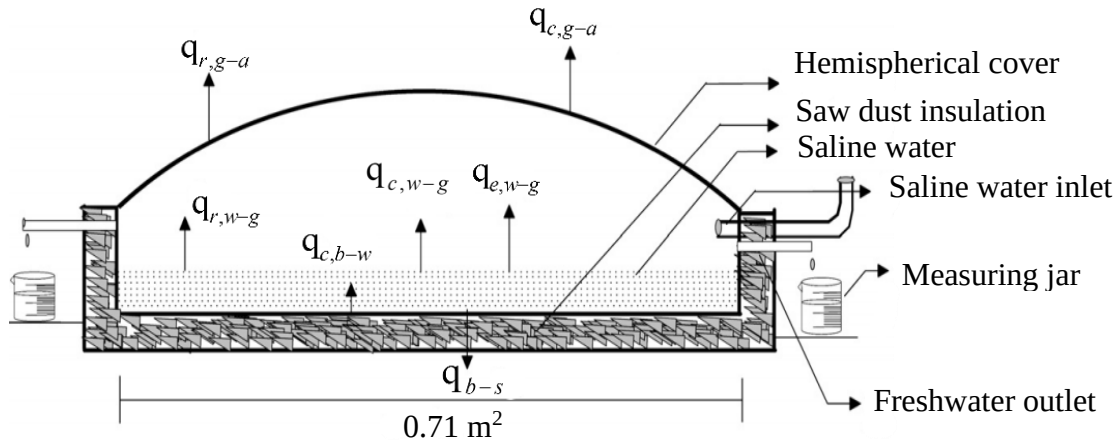


Figure 2.7: Schematic view of hemispherical solar still

Generally, the surface area of the hemispherical type was greater than a single slope solar still. Hemispherical covers have been used with the intention of rising the significant of solar energy collected by the solar still. However, when we compare the efficiency with a standard conventional solar still, hemispherical solar still gives better efficiency.

2.4.2.5 Spherical Solar Still

Spherical solar still consists of a blackened metallic plate placed horizontally at the center of a transparent cover was fabricated by (Arunkumar *et al.*, 2012). The still was covered with a polyethylene cover of diameter 0.60 m. Condensation was carried out on the top cover and distillate passes between the gap. They revealed that the distillates yield of freshwater was 2.3 L/m²/day. Figure 2.8 shows the pictorial view of spherical solar still (Arunkumar *et al.*, 2012).

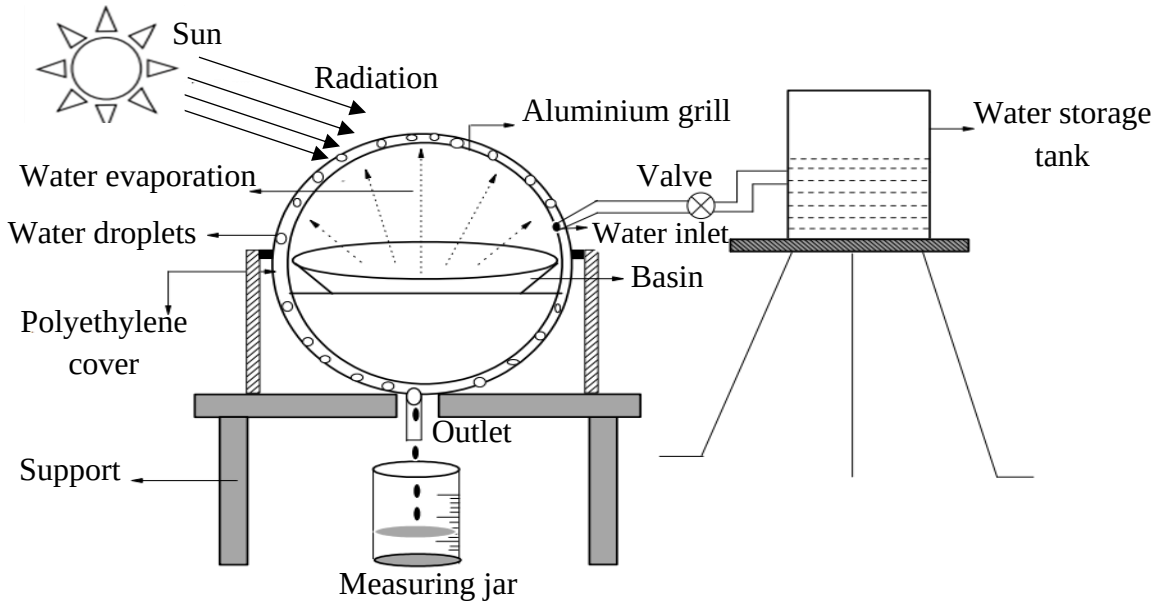


Figure 2.8: Schematic view of spherical solar still

The specialty of this still includes its simplicity, low thermal capacity, light weight, cheap cost and ease operation. Studies show that the efficiency of spherical solar still is 30% more than that of the conventional solar still.

2.4.2.6 Triangular Solar Still

A new design of solar still with a triangular top cover face for water distillation was fabricated by (Riahi *et al.*, 2015). The stills framed in triangular shape is known as triangular solar still. The still was fabricated with 50 cm length, 30 cm width and 8 cm depth. Single basin double slope solar stills of similar shapes were fabricated using stainless steel and transparent polythene film as cover. They reported that the black painted basin gave more yield than the conventional and black soil added still. The schematic view of triangular solar still is shown in Figure 2.9 (Riahi *et al.*, 2015).

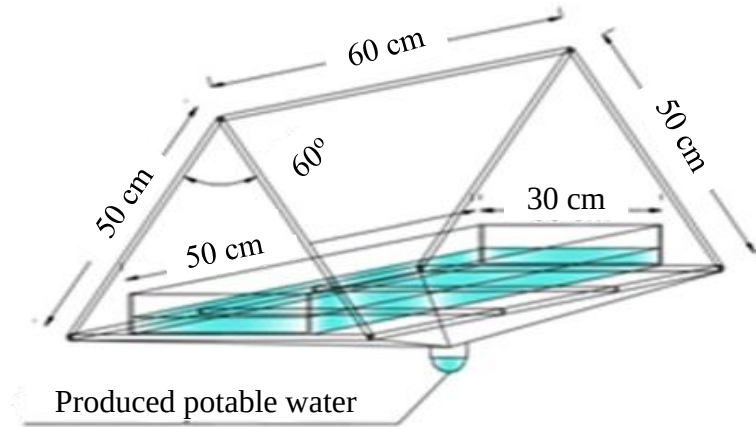


Figure 2.9: Schematic view of triangular solar still

The unique feature of this still is that, while triangular solar stills may improve yield over a single day, they have little benefit when considering yearlong performance due to radiation losses.

2.4.2.7 Tubular Solar Still

A new design of solar still with a tubular shape for water distillation was developed by (Arunkumar *et al.*, 2012). A rectangular black metallic tray of dimension 2 m x 0.03 m x 0.025 m was designed and coated with black paint. The inner and outer circular tubes were located with a 5 mm gap for the flowing water and air to cool the outer surface of the inner tube. Glass wool was used to insulate the sides of the basin. They found that the distilled yield of tubular solar still coupled with a concentrator collector was 4.5 L/m² day, respectively. The schematic view of the tubular solar still is shown in Figure 2.10 (Arunkumar *et al.*, 2012).

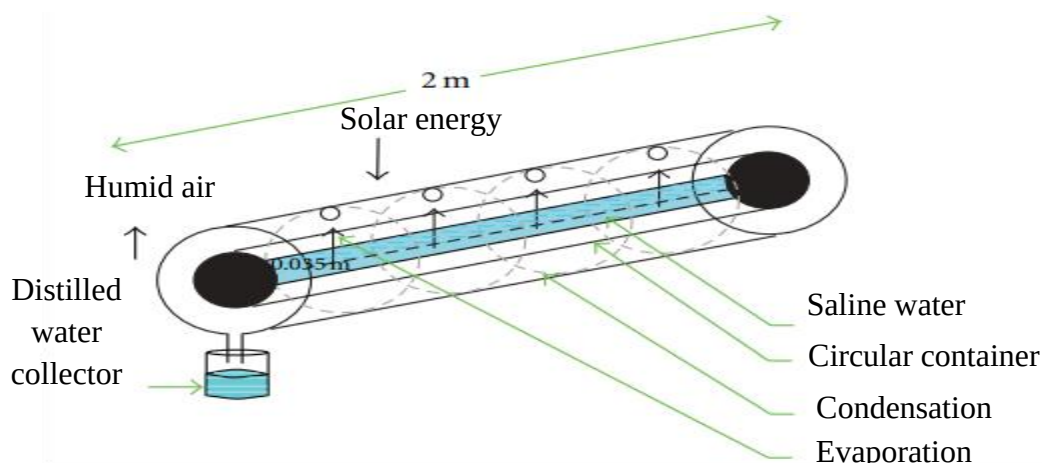


Figure 2.10: Schematic view of tubular solar still

The key finding here is that, because of the curved design of the tubular glass cover, more radiation may be collected by the glass cover compared to single and double solar stills. In tubular solar still,

there is no additional demands for sun tracking systems, when compared to conventional solar still.

2.4.2.8 DSSS Coupled with Capillary Film Condenser

Belhadj *et al.*, (2015) have investigated the performance and productivity of a double slope solar still with capillary film condenser at Adrar, Algeria. Condensation occurs at opposite front surface shown in Figure 2.11 (Belhadj *et al.*, 2015). Their findings reveal that increasing the depth of saline water and the distance between the two condensing chamber plates has the opposite effect on yield. They found that the daytime yield of the modified and conventional solar still was 7.15 and 4.52 kg/m²/day, respectively. The daily efficiency of this modified and conventional solar still was 60 and 38%, respectively.

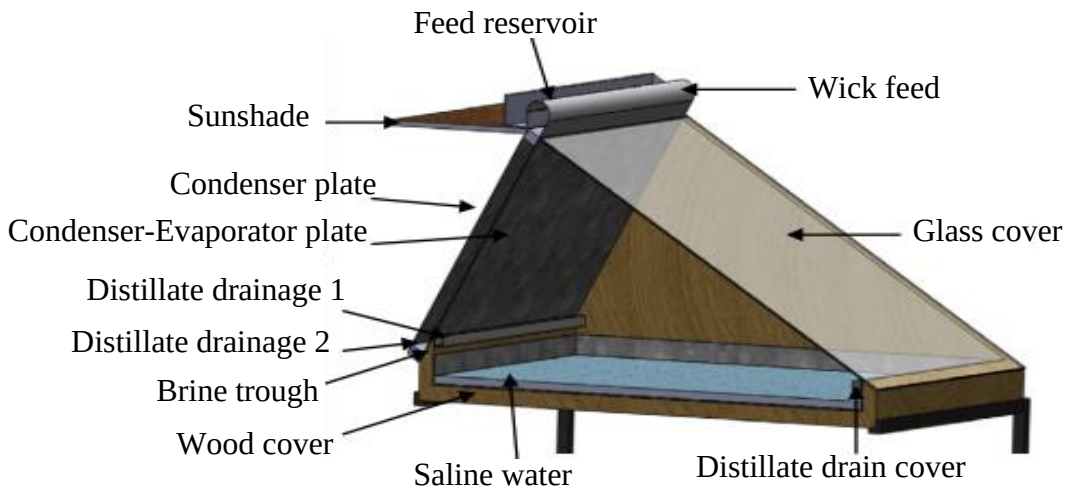


Figure 2.11: Solar distiller with capillary film condenser

2.4.2.9 Cascade Solar Still

Cascade (stepped) solar still have similar layouts to conventional stills, but their interior absorber plates have multiple steps and trays on the horizontal side. These stills have greater glass and water surface temperatures than traditional stills. Ziabari *et al.*, (2013) simulated a cascade solar still at two weather conditions of Koshk and Bandar, Iran. The still had a surface area of 1.16 m² that was exposed to the sun. To reduce heat loss, it is made of polymeric composite. The still's cavity was roofed with 3 mm glass, and the water was fed intermittently through a 1.25 cm diameter pipe. They stated that the still's daytime yield was 6.7 L/day/m², improved by 26%. Negative stairs are used in stills to extend the time the water takes to fall shown in Figure 2.12 (Ziabari *et al.*, 2013).

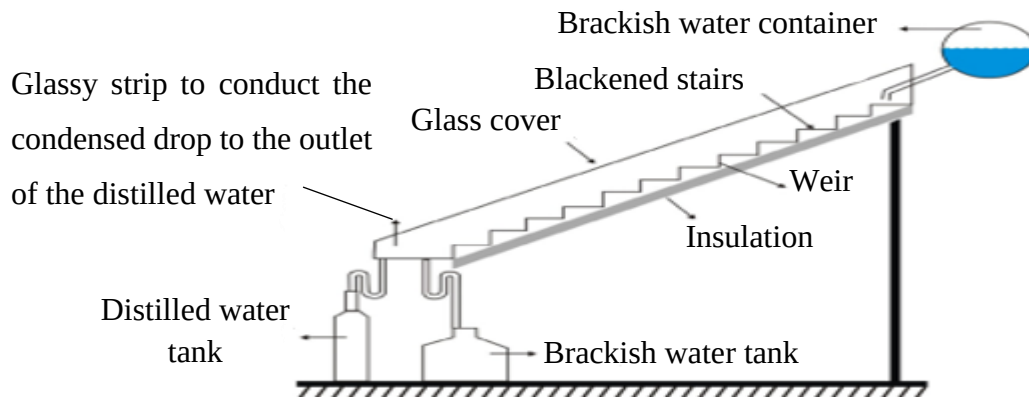


Figure 2.12: Schematic view of cascade solar still

Further to increase the distillate productivity, wick material is placed over the inclined absorber surface which maintains the uniform thickness of water and increases the area of evaporation.

2.4.3 Inclined Solar Stills

In the inclined type solar still, the whole basin is placed at an angle. The water flows from the top to bottom of the absorber surface. Aybar *et al.*, (2005) invented a still with an absorber plate and a glassy cover which makes a cavity. Galvanized steel was used to make the absorber plate black painted as shown in Figure 2.13. Their average daily yield of the still was 2.84 L/m² day.

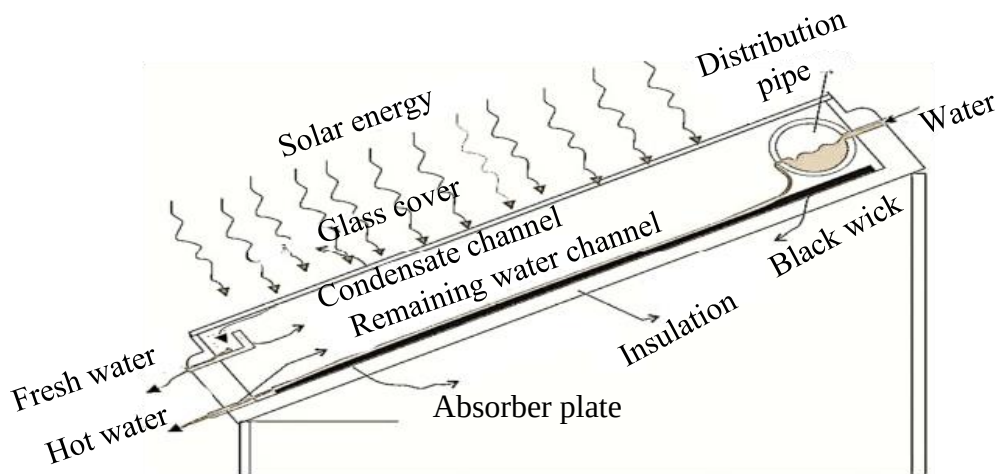


Figure 2.13: Schematic view of inclined solar still

Overall conclusion: The most important finding is that novel design solar stills are recommended to achieve higher yield. In inclined and basin types of solar stills wastage of feed water and heat loss is more which results lower productivity. Different types of stills utilize different structures

whose fabrication is very costly. Requirement of additional equipment increased the design and operational costs of the stills. This made one search for a cheaper source. In contrast, special designed solar stills are simple, release less heat and moderate production. Construction of them can be made using cheap and easily affordable material to improve the still performance in an economically feasible manner.

2.5 Parameters Affecting the Yield of Solar Stills

Several authors (Jathar *et al.*, 2021; Narayanan *et al.*, 2020) have studied that the effect of various parameters affecting the yield a of solar stills. These parameters are classified into three categories: climatic parameters, design parameters and operational parameters. The parameters affecting the yield of solar stills are summarized by (Sharshir *et al.*, 2016; Manchanda and Kumar, 2015; Muftah *et al.*, 2014) and is shown in Figure 2.14.

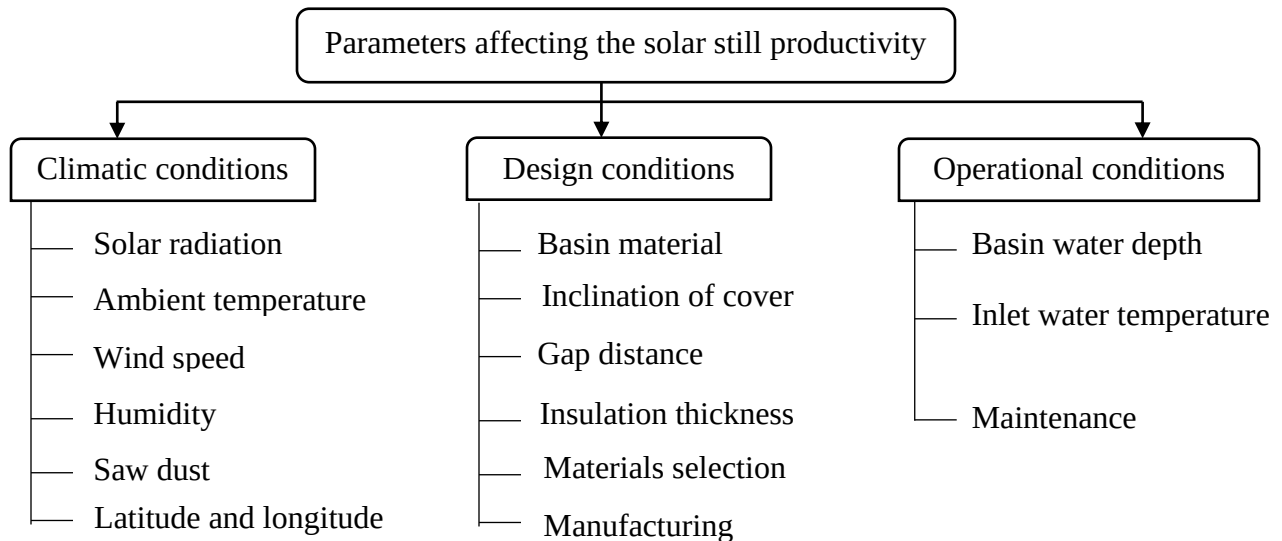


Figure 2.14: Parameters affecting the basin type of solar still productivity

2.5.1 Climatic Parameters

The climatic conditions are including ambient isolation, wind velocity, and temperature. Several researchers have studied that the solar radiation is essential and the driving energy source to the distillation process (Muftah *et al.*, 2014). Other parameters like wind speed, humidity, and ambient temperature will also affect the yield. Accumulation of sand and dust on the cover can drastically reduce the yield and the cover must hence be frequently cleaned (Jathar *et al.*, 2021). The relative humidity is a meteorological parameter that indicates how much water vapour is present in the atmosphere. It cannot be controlled but it affects the solar still output (Sharshir *et al.*, 2016).

2.5.1.1 Solar Radiation

Solar radiation is one of most significant meteorological parameters, and it is affected by the location's latitude (Narayanan *et al.*, 2020). Many studies have shown that the productivity of a solar still is highly dependent on the intensity of solar radiation because of its great effect on the rate of evaporation in the still (Jathar *et al.*, 2021; Sharshir *et al.*, 2016). The effect of solar intensity has been studied by many researchers and it is observed that the diurnal output increase with increase of total intensity falling on still in a day (Mahian *et al.*, 2017).

2.5.1.2 Wind Velocity

Wind speed may have two effects: the first effect, an increase in wind speed may accelerate heat removal from the glass cover, resulting in cooling. Thus, increasing the rate of condensation and evaporation. Increased wind speed, on the other hand, may increase the rate of heat loss from the system by convection, lowering the evaporation rate. In context of this, conflicting findings on the effect of wind on still productivity have been published in the literature (Altarawneh *et al.*, 2017).

2.5.1.3 Ambient Air Temperature

Several scholars have looked at the impact of ambient temperature variations on solar still productivity (Altarawneh *et al.*, 2017). Theoretical and mathematical modeling results reveal that simply raising the ambient temperature by 5 °C can boost total solar still fresh water output by 3% (Patel and Panchal, 2017; Muftah *et al.*, 2014).

2.5.2 Design Parameters

Design parameters entail that the various physical components of the solar still which can be controlled and improved in order to achieve optimum yield. Design conditions are the selection of the material of the still and cover, slope of the cover, gap distance between water and cover, basin material, insulation, and etc. The following design parameters affect the yield of solar stills.

2.5.2.1 Basin Material

Many researchers reported that the structural materials such as galvanized iron, copper, aluminum, wood, asbestos cement, masonry bricks, and concrete are generally used for a basin. The literature about the theoretical or experimental comparison of different basin materials' effect on the solar still yield is not prominent. To minimize reflectance loss, the basin should be made out of black or black coated materials to enhance its ability to capture solar radiation incident upon it.

2.5.2.2 Insulation

Another major factor that influences the solar still yield is the basin's insulation. The maximum amount of solar radiation required to evaporate water and transfer thermal energy is absorbed by insulation. Because it serves to limit heat escape to the environment, it is frequently found at the bottom or sidewalls. The insulation material should have a good thermal resistance as well as adequate strength to resist under the weight of the basin water (Sharshir *et al.*, 2016).

2.5.2.3 Condensing Cover Material, Thickness, and its Inclination

The impact of condensing cover material, thickness, and inclination have been reported by (Patel and Panchal, 2017; Sharshir *et al.*, 2016; Tiwari and Tiwari, 2005) to influence the yield and efficiency of basin type solar stills.

2.5.2.3.1 Cover Thickness and Material

With decreasing thickness and increasing thermal conductivity, heat transfers via the cover plate rise. Kalidasa *et al.*, (2008) revealed that a solar still with a 3 mm thick glass cover plate produces 16.5% more than one with a 6 mm thick glass cover plate. The reduced glass cover thickness boosts the incoming solar radiation's transmissivity and absorptivity product inside the basin. The material for the glass cover should be transparent and low-reflective. Because it has a higher solar transmittance for varied angles of incidence and a long service life, glass is the recommended material for the cover (Patel and Panchal, 2017). The other cheap transparent plastic materials do not possess the above required qualities (Kalidasa *et al.*, 2008).

2.5.2.3.2 Slope of the cover or Inclination

The absorption of sunlight is maximized, and condensed droplets pass into the condensate collector instead of falling into the basin water, thanks to an appropriate tilt (Narayanan *et al.*, 2020). Single slope stills are preferred for locations with latitudes greater than 20° because a double slope still will have one side shadowed for the majority of the time (Kalidasa *et al.*, 2008). For northern hemisphere locations, the inclination angle should be south, and for southern hemisphere locations, it should be north. According the findings of (Patel and Panchal, 2017), a glass cover inclination close to the location's latitude would be best for absorbing the most radiation.

2.5.2.3.3 Cover temperature

Lowering the cover temperature helps in increasing yield of solar still. When the temperature differential between the glass and the basin water rises, the natural circulation of air mass inside the glass rises as well. It improves convective and evaporative heat transfer from the basin to the cover. The rate of condensation is increased by the cooler inner glass surface. The temperature of the glass cover is lowered by a film of cooling water continually flowing over the glass or an intermittent flow of cooling water on the cover. The latent heat of condensation is captured by the cooling water, which is then regenerated by circulating it through the basin (Kalidasa *et al.*, 2008).

2.5.2.4 Effect of the Gap Distance

Reducing the gap distance between the evaporating surface and the condensing cover improves the still performance. The effect of the gap distance is much important than the effect of the cover slope. Reducing the gap distance will reduce the height of the walls of still and hence will reduce the shadowing effect of the sides. The saturated air takes less time to reach the condensing surface, allowing for more consistent and faster air circulation in the still. For the same cover slope, reducing the gap distance from 13.0 to 8 cm increases output by 11.1% (Muftah *et al.*, 2014).

2.5.2.5 Effect of Number of Covers

The number of transparent covers employed in a solar still does not enhance the output (condensing surface), because it rises the temperature of the inside cover. However, the still remains airtight. A drop of 25-35% in output was seen due to the use of a double glass cover. The still's original cost is further increased by using a double glass cover.

2.5.3 Operational Parameters

Operational conditions relate to the maintenance of the solar stills, such as regular cleaning of the glass cover to prevent accumulation of dust particles which can hinder the transmission of solar radiation through the transparent cover to the basin liner. Operational parameters include depth of water, the orientation of the still, inlet temperature of water, and etc.

2.5.3.1 Basin Water Depth

For yield enhancement, depth of basin water plays important role reported by (Jathar *et al.*, 2021; Le *et al.*, 2021; Narayanan *et al.*, 2020; Sharshir *et al.*, 2016). Depth of water in the basin affects

the performance of a still significantly at low water depth, the thermal capacity will be lower and hence the increase in water temperature will be faster resulting in higher outputs. This is because of the higher volumetric heat capacity of water (Altarawneh *et al.*, 2017). Water depth becomes important especially in the morning when low energy from the sun is available and it is required to the water quickly to producing fresh water. Hence, the only solution is to operate the still at lower depth. An increase in the water depth from 1.27 to 30 cm reduces the output by 30%.

2.5.3.2 Maintenance

When the water evaporates, salt and impurities are left behind and the basin will need proper and regular maintenance due to the buildup of lump salt masses. This will eventually fill the basin and decreases the efficiency and hygiene in the still. It would be beneficial for the still to have an access opening to perform maintenance, small repairs, and daily cleaning (Shanmugan *et al.*, 2018).

In the above-mentioned conditions, climatic conditions are not in our control to monitor. Optimum design must satisfy the requirements of the operating conditions and design conditions.

2.6 Nanoparticles (NPs)

The heat transfer mechanism and operating temperature were the two most important factors that controlled the yield of solar still. The coefficient of heat transfer is improved by improving the thermal characteristics of the base fluid. Alarifi *et al.*, (2021) have performed a comprehensive review on the impacts of nanoparticles and came to the conclusion that nanoparticles are one of the most effective methods for improving the thermal behavior and productivity of solar stills. Bait and Ameer, (2018) have studied a comprehensive review of nanofluids in enhancement of heat and mass transfer in solar stills.

Shanmugan *et al.*, (2020) conducted experimental study on single slope single basin solar still with $1.5 \times 1.5 \text{ m}^2$ was fabricated from copper sheet under Andhra Pradesh, India. They used TiO_2 nanoparticle to enhance the thermal properties of absorber plate. Their findings revealed that the average daily yield of the solar still with TiO_2 /black paint was 7.89 and 5.39 L/m^2 day through the summer and winter, respectively. They have reported that the diurnal efficiency of the solar still was 36.69 and 57.16% over the winter and summer, respectively.

Arunkumar *et al.*, (2019) studied the impact of nano-coated CuO absorber with polyvinyl alcohol in a single slope solar still (SSSS) at Chennai, India. They have revealed that the yield of CSS and

MSS was 2.144 and 2.995 L/m²/day, respectively. Their obtained outcomes exhibited that the thermal efficiency of the CSS and MSS was 37 and 53%, respectively. However, addition of polyvinyl alcohol was counterproductive, but CuO nano-coated significantly increased output.

Kabeel *et al.*, (2017) conducted a numerical study on the single slope solar still integrated with an external condenser. Also, Al₂O₃ and CuO nanoparticles mixed with water were used as heat transfer fluids in the basin. They demonstrated that the water yield was improved by 84.16% using CuO as compared to Al₂O₃. This was due to the higher thermal energy storage of CuO nanofluids than Al₂O₃ nanofluids. Sahota *et al.*, (2017) studied the incorporation of three different nanofluids, Al₂O₃, CuO and TiO₂, into the double slope solar still. They have pointed out that the diurnal yield, exergy and energy efficiency performed best with the use of Al₂O₃ water based nanofluid.

Sahota and Tiwari, (2017) experimentally studied the double slope solar still with water based TiO₂, CuO and Al₂O₃ nano-fluids. Two modes of operation were conducted experimentally with helically coiled heat exchanger and without heat exchanger. They have specified that the highest yield achieved with the use of CuO water-based nano-fluids. Mahian *et al.*, (2017) empirically studied a solar still with SiO₂ and Cu water based nanofluids. They have obtained that the Cu water based nanofluid had higher evaporation rate than SiO₂ nanofluid. Moreover, they have concluded that adding nanofluids to the basin of solar still can enhance the efficiency up to 50%.

Gupta *et al.*, (2016) studied the effect of water depth, CuO nanoparticles in the basin of single slope solar still. They have discovered that the CuO nanoparticles enhanced the fresh water yield by 22%. They have found that the overall thermal efficiency of the solar distiller with 5 cm water depth was 37.40%. Sahota and Tiwari, (2016) examined empirically the impacts of water depth, Al₂O₃ water based nanofluid in a double slope solar still. Their results showed that the productivity enhancement for 35 and 80g of the base fluid was 12.2 and 8.4%, respectively.

Elango *et al.*, (2015) experimentally tested ZnO, SnO₂, Fe₂O₃ and Al₂O₃ water based nanofluids in the single slope solar still. They have found that the highest yield enrichment was provided with Al₂O₃ nanoparticles (29.95%) relative to ZnO (12.67%) and SnO₂ (18.63%) nanofluids. Omara *et al.*, (2015) experimentally studied a wick type solar still with Al₂O₃ and CuO nanoparticles in the basin. They exposed that the wick type of solar still with CuO nanoparticle had better performance than the Al₂O₃ water based nanofluid. The results of the author reveal that use of cuprous and aluminum oxides nanoparticles enhanced the productivity by 285.10 and 254.88% respectively.

Based on the literatures and knowledge of the author, very few literatures have been reported on the impacts of nanoparticles in solar still application. The thermal conductivity of nanoparticles plays a significant role in the yield enrichment of solar still. So, additional study is required on effects of nanoparticles in solar still application.

2.7 Thermal Energy Storage

Thermal energy storage system is useful to conserve thermal energy during sunshine-off periods. Ensuring the heat loss from the basin glass cover makes better and rapid condensation for the generated vapor inside the distiller. Katekar and Deshmukh, (2020) reported that 61.60% of the solar energy used in the solar still is wasted as heat, and only 38.40% of the energy is used for water evaporation. Around 25.7% of the entire solar energy is lost from the basin liner and walls of the solar still. This is the main reason for the solar still's poor performance. As a result, by utilizing energy storage materials, these heat loss values can be reduced.

Both sensible and latent heat storage materials can be used in the thermal storage process. In an attempt to boost output, some researchers (Mohamed *et al.*, 2019) used a variety of sensible heat storage materials in solar stills. They studied different designs of solar distillation systems that were combined with various sensible heat storage materials, and the percentage productivity enhancement was reported. The phase change material (PCM) can also store thermal energy. Because phase change materials have a high energy storage capacity per unit volume and maintain a significant constant temperature for charging and discharging, they store more heat than sensible heat storage materials. Phase change material stores energy during the peak of solar radiation and releases it when the sun is not present. As a result, when the sun is not shining, the phase change materials act as a heat source for evaporating the water in the basin. Only a few studies have found that using phase change materials significantly increased the freshwater yield of solar still.

Sarhaddi *et al.*, (2017) executed a comparative analysis of exergy and energy performance of two weir type cascade solar still without and with phase change material at Zahedan, Iran. Their results exposed that the daytime energy and exergy efficiencies of solar still without phase change material were 76.69 and 6.53%, respectively. And, the yield of the still with and without phase change material were 7.05 and 6.63 kg/m² day, respectively, for a sunny day. While, for a semi-cloudy day, the daytime energy and exergy efficiencies of solar still with phase change material were 74.35 and 8.59%, respectively. Also, the yield of the still with and without phase change

material were 4.94 and 3.84 kg/m² day, respectively. They conclude that the numerical simulations were in good agreement with the experimental data of previous literatures.

Kabeel and Abdelgaied, (2016) have examined empirically the impacts of PCM on the yield of single slope solar still at Tanta, Egypt. Their obtained results show that the diurnal water yield achieved with and without PCM was 4.51 and 7.54 L/m² day, respectively, with an improvement of 67.18%. Moreover, they quantified that the diurnal energy efficiencies obtained with and without phase change material was 87.8 and 52.5%, respectively, with an improvement of 67.2%.

Shalaby *et al.*, (2016) have investigated empirically the impacts of v-corrugated absorber and PCM on the yield of the single slope solar still at Tanta, Egypt. They found that the daily yield obtained with and without phase change materials was 3.762 and 3.357 L/m² day, respectively, with an improvement of 11.7%. Furthermore, they have specified that the daily thermal efficiencies of solar still with and without phase change materials was 37.1 and 32.9%, respectively.

2.7.1 Selection of PCM

Based on previous merits of employing PCMs, a variety of raw materials are evaluated as PCMs, such as salt hydrates, paraffin waxes, sugar alcohols, and fatty acids, for the utilization of solar stills. Due to its promising properties such as low cost, chemical stability, high latent heat of fusion, minimum super-cooling, and low vapor pressure, paraffin wax is the most commonly utilized PCM material. On the other hand, low thermal conductivity is a significant disadvantage. PCM's low thermal conductivity is a major hindrance to efficient thermal diffusion and overall heat transfer rates during the melting and solidification phases. Various heat transfer augmentation approaches were designed to address this drawback. Inserting extended surfaces, such as nanotechnology additives, microcapsules PCM, metallic foams, and incorporating high conductivity fillers with phase change materials, are some of the approaches used (Yousef and Hassan, 2019).

Among all of the ways discussed above, using nanoparticles to improve the heat transfer properties of the phase change materials is the most common. Because of its uniform melting, medium storage, reliability, safety, and moderate cost (Shalaby *et al.*, 2016).

2.8 Nano-embodied Phase Change Materials (NPCMs)

Nanoparticles are being used in various application. The main downsides of phase change materials are its thermal conductivity and energy storage density. To overcome this mixing NPs

with PCM improve its thermal conductivity. Alarifi *et al.*, (2021) have reported that adding nano-powders to phase change materials enhances the heat transfer rate and changes the thermophysical properties between PCMs. Also, it increases the freshwater yield rate during low solar intensity.

Shoeibi *et al.*, (2021) analyzed the impacts of nano-enhanced PCM and nano-coated on the performance of solar stills in climatic conditions of Tehran, Iran. Al_2O_3 and CuO nanoparticles at concentrations of 0.3 and 0.1 wt% were mixed in paraffin wax and poured into 12 copper pipes. Their findings revealed that utilizing Al_2O_3 and CuO nano-enhanced PCM at a concentration of 0.3 wt%, the freshwater generation of the solar stills was boosted by 49.5 and 55.8%, respectively. After it was nano-coated with CuO, the solar still water output rate increased by around 5.7%. Using Al_2O_3 and CuO nano-enhanced phase change material at a concentration of 0.3 wt% and nano-coated, the cost per liters of the solar still were 0.1 and 0.104\$/L, respectively.

Shanmugan *et al.*, (2018) analyzed the impact of incorporating Al_2O_3 nanoparticles with wick materials and PCM (stearic acid) as thermal energy storage in single slope solar still at Chennai, India. Energy balance equations for the moist air inside the still, glass cover and wick material was exhibited to get thermal analysis. Their daily accumulated productivity of a combination of PCM and nanoparticles for Summer and Winter was 7.460 and 4.120 kg/m² day, respectively. They conclude that the experimental and theoretical results were validated and shows a good agreement.

Regarding the literature and knowledge of the author, very few literatures have been reported using nano embodied PCM in solar still application. Thus, the present study bridges the above-mentioned research gap by examining empirically the impacts of NPCM in solar still application.

2.9 Energy, Exergy and Economic Analysis

Only few researchers conducted various analyses on passive solar stills such as thermal analysis, exergy analysis and parametric analysis. Exergy and energy analysis are utilized to assess the performance of solar stills, by evaluating the heat transfer (gaining or losing) activity between the solar still and its environments. The exergy destruction in various components of the solar still have been analyzed and a solution was suggested by (Sharshir *et al.*, 2018).

Vikram *et al.*, (2021) experimentally investigate the effect of a V-shape concentrator integrated with solar still. Their obtained freshwater generation of the MSS was 4.89, 5.10, and 5.47 L/m² day, while for CSS was 2.91, 3.27, and 3.73 L/m² day at the water depths of 0.03, 0.02, and 0.01

m, respectively. They revealed that the diurnal exergy and energy efficiency of CSS were 0.97, 1.5, and 1.9%, and 29.4, 33.5, and 38.5% in the case of 0.03, 0.02, and 0.01 m water depth, respectively. The addition of concentrator significantly amplified the exergy and energy efficiency by 2.8, 3.3, and 3.8%, and 44.9, 51.7, and 57.4% for the corresponding water depths of 0.03, 0.02, and 0.01m. The economic analysis of the freshwater cost per liter for modified and conventional solar still were 0.0117 and 0.0102 \$ correspondingly, at a water depth of 0.01 m.

Sharshir *et al.*, (2020) performed experimental study of three modifications on the traditional pyramid distiller (TPD) with basin area of $0.75 \times 0.75 \text{ m}^2$, at Kafrelsheikh, Egypt. They improved total freshwater productivity with use of v-corrugated absorbers, wick materials with the v-corrugated, and copper oxide nanofluid with wick and v-corrugated absorbers were 28.38%, 45%, and 72.95%, respectively, compared to the TPD. Their accumulated freshwater for MSS and CSS reached was 5 and $2.8 \text{ L m}^{-2} \text{ day}^{-1}$, respectively. The MSS shows the best improvement in terms of daily exergy and energy efficiency by 93 and 60.5%, respectively, compared to TPD. Finally, the results of cost analysis reveal that the MSS gives the lowest cost compared to TPD.

Yousef *et al.*, (2019) executed analysis of energy, exergy and economic of single slope solar still. Three cases were considered to evaluate the performance of single slope solar still under Egypt climatic conditions: conventional solar still (CSS), modified solar still (MSS)-1: with hollow cylindrical pin fins, MSS-2: with steel wool fibers. Their results reveals that the diurnal yield of MSS 1 and 2 enhanced by 16 and 25%, respectively in comparison with conventional solar still. The maximum energy efficiencies of CSS, MSS 1 and 2 were 42, 45.5, and 52.5%, respectively. The MSS 1 and 2 show an increment of the daytime exergy efficiency of 14 and 23%, respectively. Besides, they revealed that the economic analysis of costs per liter per square meter for the CSS, MSS 1 and 2 were 0.0427, 0.0416, and 0.0343\$, respectively.

Sharshir *et al.*, (2018) empirically evaluated exergy and energy in various components of solar still with micro/nanoparticles. Their outcomes exposed that the diurnal energy efficiencies of MSS with CuO and graphite were 38.61 and 41.18%, respectively, while for CSS was only 29.17%. Their daily yield of the modified was improved by 32.35 and 41.18% for CuO and graphite, respectively, compared to conventional. Also, the diurnal exergy efficiencies of MSS were 3.78 and 4.32% for CuO and graphite respectively, while for CSS was 2.63%. The authors conclude that the exergy and energy efficiency of modified solar still were higher than conventional one.

Ranjan *et al.*, (2016) executed exergy and energy analysis of a single-slope solar still under Indian climatic conditions. Their daily accumulated freshwater produced was 4.17 L/m² day. The findings of the authors show that the exergy and energy efficiency of the solar still was 4.93 and 30.42%, respectively. Aghaei *et al.*, (2013) performed theoretical and experimental investigation of the exergy and energy efficiencies of cascade solar still. The maximum exergy and energy efficiencies obtained was 10.5 and 83.3%, respectively. Their theoretical results are in good agreement with the experimental value.

Regarding the literature and knowledge of the author, very few researchers analyzed and discussed the exergy and energy analysis in saline water surface of the solar still. Majority of theoretical investigations on solar still reported in the literature have not taken into account the heat capacity of the basin and glass cover for the mathematical model. So, additional study is required for analyzing the various components of solar still and its performance. The exergy loss during the day time includes the exergy destruction in the main components of the solar still like basin plate, brine water, glazier plate and insulation material.

2.10 Design Improvements and Modifications of Passive Solar Stills

Various improved designs and modifications of a solar still have been made by several researchers all over the world to make the features attractive, improve the performance, feasibility and adaptability. A number of theoretical studies were also conducted. Researchers use different techniques to increase the production capacity of solar still. This section briefly introduces the important work carried out in this area.

Abdelgaied *et al.*, (2022) executed experimental investigation on the performance improvement of modified stepped solar distillers with basin area of 1.08 m² (120 × 90 cm²) under Tanta, Egypt climatic conditions. The authors modified that the conventional solar still by combining three effective hybrid modifications on the design; CuO nano-paint coating, interior mirrors, and phase change material below the steps. Their experimental results show that the diurnal yield achieved by modified solar still was 9.79 L/m²/day compared to 4.15 L/m²/day achieve by conventional solar still, with an enhancement of 135.9%. They found that the thermal efficiencies of modified and conventional solar still reached was 78.8 and 33.3%, respectively, with an enhancement of 136.6%. Also, the exergy efficiencies of modified and conventional solar still reached was 7.96 and 2.77%, respectively, with an enhancement of 187.4%.

Attia *et al.*, (2022) have tested the influence of cover cooling and nanoparticle alterations on the performance of hemispherical solar stills at Algeria. The best concentrations of CuO nanoparticles were examined using a concentration of 0.1, 0.2, and 0.3% wt. Their experimental results reveals that the employment of glass cover cooling and CuO nanoparticles at concentrations of 0.3% represents the best option to achieve the maximum cumulative output of hemispherical solar stills. They reported that the diurnal yield achieved by modified and conventional solar still was 7.9 and 3.85 L/m²/day, respectively, with an enhancement of 105.2%. The daily efficiency of modified and conventional solar still was 75.92 and 37.68%, respectively, with an improvement of 74.2%.

Younes *et al.*, (2022) performed experimental investigation on the performance enhancement of solar still with 0.5 m² from a galvanized steel under Kafrelsheikh, Egypt climatic conditions. They found that the freshwater productivity of solar still employing rotating discs, CuO nano-enhanced paraffin wax mixed with emerging fins and reflectors enhanced by 184% over the conventional solar still. Their results daily accumulated freshwater produced from modified and conventional solar still was 11.800 and 4.150 L/m² day, respectively. They quantified that the thermal efficiency of the modified and conventional solar still was 56.5 and 44.5%, respectively. The assessed cost per liter of freshwater produced from conventional and modified solar still was 0.024 and 0.014 \$, respectively.

Abdullah *et al.*, (2020) researchers analyzed the impact of using reflectors, nano-paint coating, and nano-enhanced phase change material on the performance of single solar still with area of 0.5 m² (1 × 0.5 m²). They reported that the yield of the freshwater was improved by 108% when using reflectors, CuO nanoparticle black paint, and nano-enhanced phase change material. They found that the diurnal yield of the modified and conventional solar still was 5.0 and 2.4 L/m² per day, respectively. Also, the thermal efficiency of the modified solar still was 51.5%.

Gupta *et al.*, (2017) experimentally studied the single slope solar still for saline water distillation under Jabalpur, India climatic conditions. Three modifications were investigated: the side walls of the solar still painted white, cover cooling by sprinkler arrangement and Cu₂O nanoparticle in the basin. They found that the distilled water in modified and conventional solar still was 4 and 2.9 L/m²-day, respectively. Their obtained efficiency of modified and conventional solar still was 34 and 22%, respectively. Their experimental analysis shows that with the design amendments overall efficiency was 54.54%.

2.10.1 Design Amendments in Passive Solar Stills

In this review, new designs of components are categorized into four processes: solar radiation collection, heat energy absorption, heat storage, and water vapour condensation. It covers all the steps that take place in the solar thermal desalination process to generate drinking water. The new designs and elements for each category are reviewed in separate sub-sections.

2.10.1.1 Different Modifications of Solar Radiation Collection

Le *et al.*, (2021) have found that adding an internal reflector to a stepped solar still can increase daily yield and efficiency by up to 75 and 56%, respectively, whilst adding a sun-tracking device to a passive solar still increased daily yield by up to 22%. Mohsenzadeh *et al.*, (2021) carried out a theoretical review on passive solar still performance improvements and water cost reductions related to new designs and changes suitable for remote locations. They have addressed many knowledge gaps and future research possibilities in order to boost the advancement of passive solar stills. The authors conclude that the internal and external reflectors need to be placed in the best direction closer to the passive solar still to improve solar radiation.

Agonafer, (2020) carried out the experimental analysis in Debre Berhan, Ethiopia on double slope solar still with $2 \times 1 \times 0.3$ m has been designed with galvanized iron sheet and used reflector which made of aluminum to increase the effect of radiation on the basin surface. Researcher used 20 – 30 mm size of black basalt on the surface of the basin act as a storage medium for enhancing the quantity of distillate water. Authors show that the system produces approximately 6 L/m² day.

Gnanaraj and Velmurugan, (2019) have investigated three solar stills: conventional still, still with heat storage materials, and still with external reflector, which has identical dimensions of 1 m × 0.6 m × 0.4 m were fabricated with an iron sheet of 2 mm thick. The authors conclude that the productivity of the still with heat storage materials was 23.08% higher than the conventional still, and the productivity rise in the still with a reflector was 62.97%. To conclude, modifications in the single basin double slope solar still was effective in augmenting the production of the still.

2.10.1.2 Different Modifications in the Basin or Heat Energy Absorption

Le *et al.*, (2021) conducted the review of passive solar stills with rectangular basins, fins basins, corrugated basins, wick type, cylindrical shape and stepped shape basins with a change of top cover shapes. The findings of this review conclude that cylindrical basin liners have better

performance and provide higher freshwater production compared to other types of basin liners. Fin absorber, corrugated, stepped type, and inclined shapes have effective performance for augmenting the performance of passive solar still. Mohsenzadeh *et al.*, (2021) have reported that among the different methods of basin design improvement, the concave wick basin had a significant impact on the passive solar still, with a 95% rise in water output and a 20% decrease in unit water cost.

Saravanan and Murugan, (2020) have executed the analyzes of square pyramid solar still incorporated with different types of vertical wick material under Kakinada, India climatic conditions. They reported that the maximum distillation efficiency obtained at a water depth of 2 cm depth was 29.57%, which is higher than 28.4, 27, 25.9, and 24.2% at a water depth of 3, 4, 5, and 6 cm, respectively. Furthermore, experiments were conducted at 2 cm water depth-integrated with various wick materials to improve square pyramid solar still productivity. They further reported that the diurnal efficiency of solar still with woollen fabric was 37.4%, which was greater than that of conventional solar still, polyester cloth, terry cotton, and jute cloth, which was 35.3, 28.4, 19.3, and 8.2%, respectively.

2.10.1.3 Different Modifications of Heat Storage

Abdullah *et al.*, (2021) amended the thermal behavior of solar still tray employing wick corrugated absorber, nano-enhanced phase change material and photovoltaic-powered heater. Abdullah *et al.*, (2021) amended the thermal behavior of storage materials in solar stills with wick corrugated absorbers, by applying CuO nanoparticles were added to paraffin wax. Mohsenzadeh *et al.*, (2021) researchers have recommended that placing the nanocomposite phase-changing material under the basin and embedding fins to boost the heat storage effect.

Abdullah *et al.*, (2020) have studied the effect of CuO nano-coating, internal mirrors, and nano-embodied phase change material on the thermal behavior of the solar still trays. In comparison to the conventional solar still, they discovered that daily freshwater production increased by nearly 108%. Mohamed *et al.*, (2019) explored the effect of fine black stone used as a porous absorber on the solar stills freshwater production rate. In the solar still, a black stone with grain sizes of 2, 1.5, and 1 cm was employed. They found that fine stone with particle sizes of 2, 1.5 and 1 cm increased the exergy efficiency of solar stills by 123, 104.4 and 65%, respectively. Moreover, utilizing fine stone with particle sizes of 2, 1.5 and 1 cm, the freshwater generation of solar stills increased by 33.37, 27.86 and 19.81%, respectively.

2.10.1.4 Different Modifications Water Vapour Condensation

Prakash and Jayaprakash, (2021) have performed design and fabrication of a novel stepped manifold basins in a pyramid solar desalination system under Coimbatore (11° N latitude), India climatic conditions. The experimental setups were made from mild steel, where the area of each basin gradually changes towards the surface of the condensed glass. The authors conclude that the theoretical results are found to be well agreed with the experimental observations. The efficiency and diurnal output of modified pyramid solar desalination system were obtained at 50.85 and 3.25 L/m² day, respectively, which is greater than that of the conventional pyramid solar still.

Nayi and Modi, (2018) have performed reviews of the various arrangements and configurations available for the development of pyramid shape solar still, along with various methods for improving their performance. The researchers conclude that pyramid-shaped solar still is more effective than conventional solar still, eliminating the need for a tracking mechanism and reducing the sidewall shading effect. Expansion of wick material across the basin area continued to have an important impact on increasing system performance up to 50.25% daily efficiency. To improve the evaporation rate, the use of forced convection inside the system is recommended which leads to a noted increase in daily productivity of up to 25%. To maximize the daily yield, the tilt angle of the glass cover should be kept the same as the local latitude. The efficiency of exergy and energy increases as the saltwater depth decreases.

Vala and Kanabar, (2017) have executed reviews of the various researcher investigations of different shapes of solar still for getting a maximum yield of production. The authors conclude that pyramidal shape solar still has an appropriate geometric shape of all among shape and increase up the production of freshwater compared to other shapes. Also, conclude that the modified shape is affected by the various parameter for enhancing more efficient than single slope solar still.

Arunkumar *et al.*, (2012) compared the different designs of solar stills. They developed seven different designs such as pyramid solar still, double basin glass solar still, hemispherical solar still, concentrator coupled single slope solar still, tubular solar still, spherical solar still, and tubular solar still coupled with pyramid solar still. The performance of each design was tested under same climatic conditions. From the experimental results they reported that, tubular solar still coupled pyramid solar still showed the maximum amount of yield due to the concentrator effect.

2.11 Enhancement Methodology

To improve the productivity of a solar still, the amount of solar energy received at the absorber plate and the rate of heat rejection at the condenser glass cover must both be increased. To achieve this, many investigators altered the design of solar still as shown in Figure 2.15.

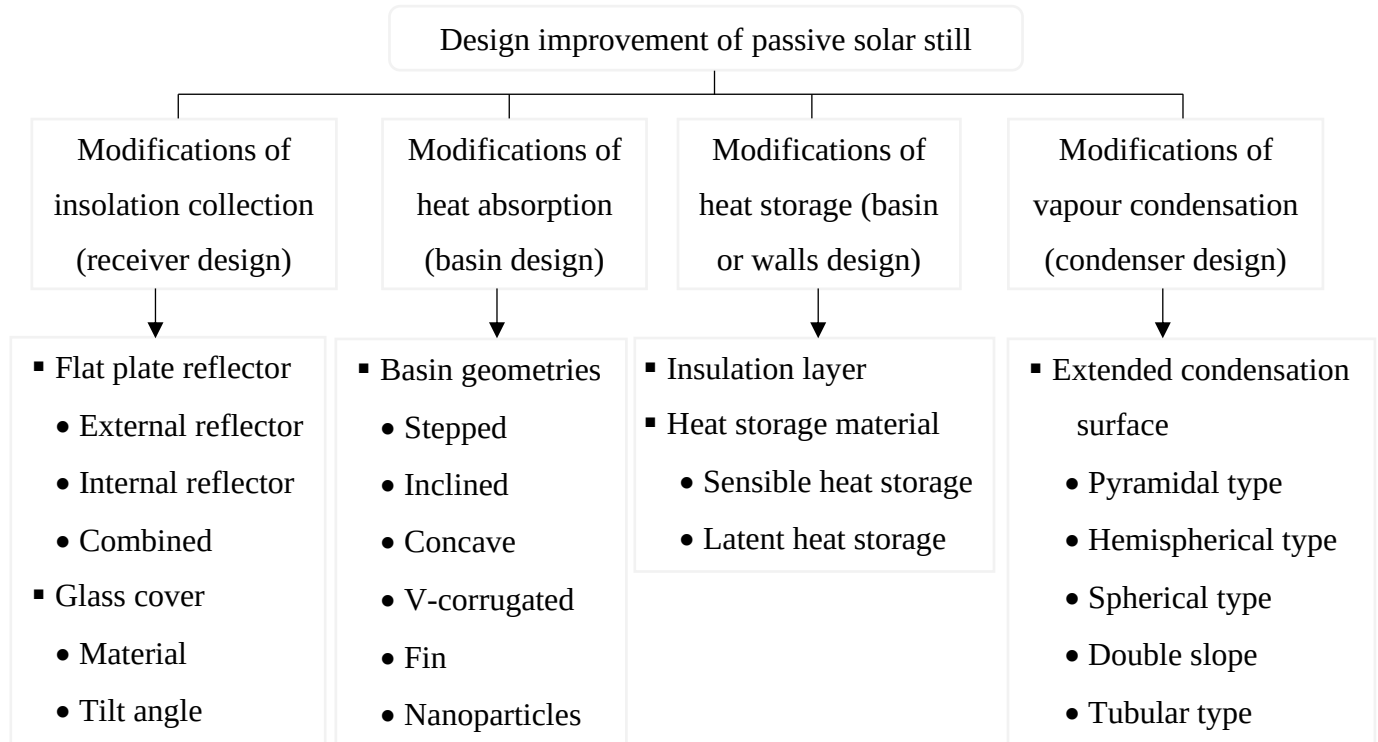


Figure 2.15: Design amendments in passive solar stills

2.12 Water Quality Analysis

Jobrane *et al.*, (2022) have conducted experimental study to test the quality of the produced water and to assess the pollutants removal effectiveness of the designed wick solar still. They reported that the pH, TDS values, and electrical conductivity of 7.9, 49100, and 49800 in the saline water were reduced to 6.9, 15 mg/L, and 17.5 μ S/cm, respectively, in the distilled water. Shoeibi *et al.*, (2021) have examined the quality parameters of distilled and saline water of solar stills. They found that the pH, TDS values, EC, total suspended solids (TSS) of 7.92, 810, 1650 and 7.1 in the saline water were reduced to 7.21, 45 ppm, 102 ms/cm, and 0.5 ppm, respectively, in the distilled water which was in the acceptable range from the solar still science point of view.

Agonafer, (2020) studied the quality parameters of distilled and saline water of solar stills. Researcher found that the pH, TDS, electrical conductivity and total suspended solids values of

7.59, 759.7, 85.3 and 4.0 in the saline water were reduced to 5.08, 84.72 mg/L, 88.5 $\mu\text{S}/\text{cm}$, and 1.02 ppm, respectively, in the distilled water. Shanmugan *et al.*, (2020) have examined the pH, TDS values, EC, Salinity of 9.1, 185.4, 5.20 and 148.3 in the saline water were reduced to 6.1, 89.6 mg/L, 0.31 $\mu\text{S}/\text{cm}$, and 71.1 ppm, respectively, in the distilled water. Sharshir *et al.*, (2020) have analyzed the TDS and pH value of 1350 and 8.6 in saline water were decreased to 95 mg/L and 7.1, respectively, which is satisfactory based on World Health Organization (WHO).

Omara *et al.*, (2015) have measured TDS and PH value in a water sample before and after the distillation procedure. The pH and TDS values of 8.9 and 980 in the saline water were reduced to 7.2 and 90 mg/L, respectively, in the distilled water. The authors concluded that the output distillate water quality lies in the acceptable range according to the WHO. Riahi *et al.*, (2015) have analyzed the pH and TDS value of 7.25 and 380 in brackish water were decreased to 6.63 and 250 mg/L, respectively, which is within the acceptable range of WHO.

2.13 Proposed Solar Desalination Techniques Identified from Literature Review

From the aforementioned literature, there are various types of designs such as a conventional, double slope, pyramid, inclined wick, cascade, and so on. All of these systems provide different yields and have different thermal efficiency. Moreover, some designs require extra components such as condensers, collectors, and reflectors to improve solar still yields and efficiency. However, this raises the cost of their investment. Also, some systems have great production, but their thermal efficiency is low due to an increase in the area exposed to solar radiation. The shadow effect is a major drawback of several types of conventional solar stills.

Furthermore, the pyramid solar still has been implemented to overcome the limitations of conventional solar still. Pyramid solar still, which is the upper glass cover in the shape of a pyramid, is recognized as one of the best methods for improving freshwater yield by utilizing solar energy. Square shape, triangular and rectangular shape are the three different structures of upper glass cover. The following are the key features of the pyramid solar still over the standard one:

- There is no need to identify the direction of solar radiation because all upper regions of the body are exposed to it at all times and in all places. Conversely, the traditional type must determine solar radiation trends in order to maximize the amount of solar radiation that enters the distiller.

- The shading results for walls are significantly reduced when a pyramid solar still is utilized than when a traditional type is employed.
- Considering the same area of the basin, because of the larger condensation area, the vapor condensation in the pyramid distiller is greater than the conventional one.

2.14 Summary of Literature Survey

All performance data from prior research, as well as the design specifications, were examined and presented in tables to provide a comprehensive review in the area of solar still. Table 2.1 shows summary of the yield and efficiency of various designs of solar stills from prior study.

2.15 Research Gap and Outcomes of Literature Survey

From the above review, it is clear that there are many techniques available to increase the yield of the solar still. However, it is found that the yield of conventional solar distillation system is low. The claimed efficiency of a conventional solar still was in the range of 30 - 45%, and the output was less than 5 L/m² per day. This yield can be improved by controlling the operating parameters. Regarding the literature and knowledge of the author, the following research gaps are specified.

- Analysis such as energy balance using the second law of thermodynamics were not fully mentioned in the literature. For pyramid solar still, insufficient investigations were found in the literature on exergy analysis compared with energy analysis.
- Solar radiation was not fully utilized inside the water basin because some of it was absorbed by the black painted vertical wall above the upper water surface. No attempts had been made in the use of nanocoated with v-corrugated absorber to absorb solar radiation.
- Analysis such as heat losses were not fully explored in the majority of the literature. There is a lack of works that study nano-embodied PCM in solar still application. No attempts had been made to study the impact of using NPCM combined with nanocoated and v-corrugated absorber on enhancing the thermal performance of the pyramid solar still.
- A very limited number of papers discuss about the quality of desalinated water obtained from the solar still.

Additional study is required to improve the yield of solar still and to recognize the work of different operating parameters. Thus, the present study bridges the aforementioned research gap through an experimental and theoretical investigation.

Table 2.1: Summary of the literature review in table

Authors	Classification	Analysis	Efficiency (%)	Yield (L/m ² day)	Modifications
Abdelgaied <i>et al.</i> , (2022)	Stepped SS	Experimental	78.8%	9.79	CuO nano-coating, interior mirrors, and PCM
Attia <i>et al.</i> , (2022)	Hemispherical SS	Experimental	75.92%	7.9	Cover cooling and CuO nanoparticles
Younes <i>et al.</i> , (2022)	Single slope SS	Experimental	56.5%	11.8	Nano-enhanced PCM with emerging fins, adding rotating discs, and reflectors
Abdullah <i>et al.</i> , (2020)	Single slope SS	Experimental	51.5%	5.0	Reflectors, CuO nano-coating, and PCM
Shanmugan <i>et al.</i> , (2020)	Single slope SS	Experimental	57.16%	7.89	TiO ₂ nanoparticles mixed with black paint
Sharshir <i>et al.</i> , (2020)	Pyramid SS	Experimental	60.5%	5.0	v-corrugated, wick materials, nanocoating
Arunkumar <i>et al.</i> , (2019)	Single slope SS	Experimental	53%	2.995	CuO nano-coated and polyvinyl sponge
Shanmugan <i>et al.</i> , (2018)	Single slope SS	Experimental and Numerical	-	7.46	Wick materials, Al ₂ O ₃ nanoparticles with black paint and PCM (striaic acid)
Gupta <i>et al.</i> , (2017)	Single slope SS	Experimental	54.54%	4.0	Sprinkler attachment and nanoparticles
Sarhaddi <i>et al.</i> , (2017)	Cascade SS	Experimental and Numerical	76.69%	7.05	With and without phase change materials
Kabeel and Abdelgaied, (2016)	Single slope SS	Experimental	87.8%	7.54	With and without phase change materials
Shalaby <i>et al.</i> , (2016)	Single slope SS	Experimental	37%	3.762	V-corrugated absorber and PCM

CHAPTER THREE

MATERIALS AND METHOD

This chapter introduces overall design of the study, which includes the methodology adopted for carrying out the work and various phases of this research. Details of the work done in each phase along with the tools, techniques and models used have also been covered in detail here.

3.1 Method

This study was carried out with the purpose of developing an effective and efficient water distillation system for desalination of saline water with low cost. The methodology followed to achieve this study was based on the objectives formulated. This study was conducted by reviewing the scientific literature and then performing theoretical and experimental analysis with the solar radiation of Fantale's and Adama climatic conditions, respectively. The study begins by working out the quantity of drinking water required for a family in rural areas. Subsequently, the system has been designed to make available this quantity of water and system components such as basin material, absorber and a compartment to collect distilled water have been designed. To ensure an effective and cost-efficient design, experimental and theoretical analysis were performed. Then, the designed components were fabricated and tested by varying different parameters.

The influence of several parameters on the proposed solar still yield was investigated. These parameters include basin water depth ranging from 3 to 1 cm with decrement of 1 cm, the effect of proposed modifications (such as v-corrugated absorber, CuO nano-coating, internal reflectors and nano-enhanced phase change material) and varying concentrations of nanoparticles. To increase the surface area of evaporation subjected to solar radiation use of v-corrugated absorber was analyzed. To increase the rate of solar insolation and absorptivity inclusion CuO nanocoated on the absorber plate was examined. Enclosure of nano-embodied phase change material which is used as energy storing materials was examined. A critical experimental comparison of both conventional and modified pyramid solar still was conducted and analyzed in terms of various operating parameters and economic viability. Finally, a mathematical model was developed and validated using experimental data.

The overall progress of this present study starting from proposal writing to completion of thesis, methodology proposed and implemented was presented in Figure 3.1. The following methodology was followed to achieve the objectives of the study.

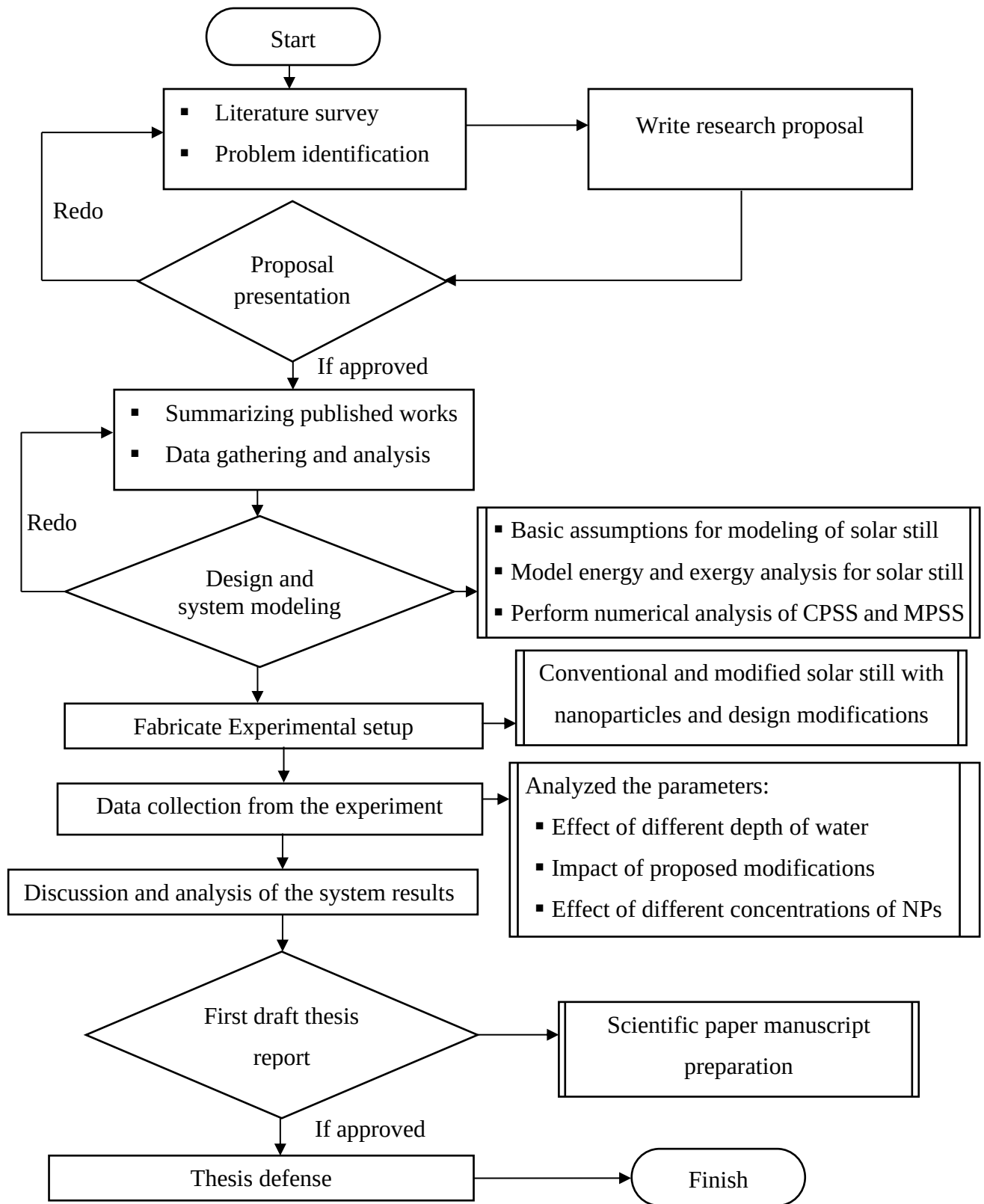


Figure 3.1: Flow-chart for the methodological approach and progressive steps

3.1.1 Literature Review

First, a review of literature on finding various solar distillation techniques was performed. Through literature study, review of available solar desalination, various techniques and approaches used for design and manufacture of solar systems was studied along with their methodology, results, efficiency, and yield levels. Materials used for construction of solar still was reviewed. Gathering as much information about passive solar still, parameters that affect the yield of solar still, design parameters, and parameters that influences the rate of evaporation and condensation of passive solar stills from various research papers and journals was performed. With the information gathered, yield improvements of passive solar still was designed to further optimize the system.

3.1.2 Data Collection

The study begins with an assessment of daily requirement of drinking water by an average rural family and the amount of saline water that must be evaporated to produce the required quantity of purified drinking water. From the quantity of water to be evaporated, then the researcher finds how much heat would be required and for this what should be optimum design to provide maximum yield of water. Fantale's and Adama solar radiation data and ambient temperatures were collected from Ethiopia meteorological agency. The physical and chemical properties of water before distillation and after distillation like pH, total dissolved solids, electrical conductivity was measured. In addition, other necessary data and materials were collected from the experimental analysis, literature review, reputable references, and available sources.

3.1.3 Physical Concept

In physical concept, a schematic drawing of the system integration and all the components are represented after the design modifications of a solar still. The 3D or pictorial view of the proposed solar still was sketched with SOLIDWORKS 2021 Software. To understand the process of the experimentation, block diagram of the experimental setup along with the measuring instruments and other accessories were sketched. The system flow process and the working principle were discussed to understand the concept of the system.

3.1.4 Mathematical Model

A mathematical model was developed to predict the amount of water to be evaporated and time required for evaporation depending upon the intensity of solar radiations and by varying different

parameters. To create a mathematical model of the problem to be solved, assumptions, defining basic variables and knowing what fundamental principles applicable (like mass and heat energy balance) on the system is needed.

3.1.5 Validation

Based on the mathematical modeling, prototype of the best solar still was developed. Experimental investigation was conducted to validate the mathematical modeling. In addition, comparison of the maximum yield of modified and conventional solar still were made to analyze the best parameters and to study the effect of various concentration of nanoparticles on the yield improvement.

3.2 Water Sampling

Ethiopia has a tremendous source of water, but many water sources are not suitable for family needs. Lake Basaka is found around Fantale. The water available around Fantale (Lake Basaka) is too salty whose salinity is $EC \sim 3.17$ mS, $pH \sim 9.73$ and poor water quality (for more detail, section 6.9 and Appendix-F). Hence, they cannot be used for drinking purpose and many applications. In order to reduce the salinity and make them potable water, solar desalination technology was applied. Water sample was collected from Lake Basaka at sampling point by using plastic jugs (jars) and travelled to Adama for the sake of experiment. The samples of saline and distilled water were collected in 2 L plastic bottles to evaluate the quality of water and different physio-chemical parameters at Department of Chemistry Laboratory, ASTU. Samples of saline water poured from Lake Basaka was shown in Figure 3.2.



Figure 3.2: Samples of saline water poured from Lake Basaka

CHAPTER FOUR

DESIGN AND THEORETICAL ANALYSIS OF SOLAR STILLS

Design of solar stills, energy and exergy equations used for predicting the thermodynamic performance are explained in this chapter. A large part of solar radiation which falls on the still is absorbed by the blackened region of the basin. A small portion of the radiation is reflected back from the surface of the water and basin. Most of the energy absorbed by the basin is transported to the water. A small fraction is lost to the bottom through conduction and convection in the basin. Heat absorbed by water is used for evaporation and transferred to the glass as vapour. Another part of the heat from water is transferred to the glass cover by free convection using air. The remaining part is radiated. Some heat is accumulated as heat in the still and water. The water is condensed on the bottom surface of the glass cover. This is the condition needed by the still for water production.

4.1 Analysis and Estimation of Solar Radiation Intensity

The design of a solar still system requires a precise knowledge concerning the availability of global solar radiation and its components at the location of interest. To calculate the total amount of solar energy incident on the solar collector, solar radiation intensity data is essential. In developing countries such as Ethiopia, due to the absence or malfunction of measuring instruments, reliable solar radiation data are not available. Estimation of solar radiation intensity by applying empirical model using climatological data is used to overcome the problems related with solar radiation measuring instrument. The output of the solar radiation model is the total captured radiation which can be used as an input to the energy and mass balance model.

4.1.1 Data Collected from Meteorology

The meteorological weather data like geographical coordinate of Fantale, sunshine hour duration, and ambient temperature are the most important requirements to estimate solar radiation. Geographical coordinates of Fantale station: Latitude (ϕ) 08° 59' 00" N = 8.983°; Longitude 39° 56' 00" E = 39.93°; Altitude = 946 m above sea level. In this study, the weather data of Fantale district for ten years average climatic conditions (from 2012 up to 2021) was collected from National Metrological Agency, Adama branch, Ethiopia. The collected data includes duration of sunshine hours, wind speed, maximum and minimum temperature.

4.1.2 Sunshine Hour Duration and Wind Speed

The length of time that the ground surface is irradiated by direct solar radiation is known as sunshine duration, and it has been used to characterize the climate of various locations. The obtained sunshine duration was used to theoretically estimate the global solar radiation on the needed surfaces. The monthly average sunshine duration and wind speed of Fantale Woreda ten years ago (from 2012 to 2021) was given in Table 4.1 and shown in Figure 4.1.

Table 4.1: Estimation of monthly average daily sunshine hour and wind speed of Fantale

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sunshine hours	9.25	9.52	9.02	8.24	8.70	8.14	7.06	6.96	7.37	8.60	8.84	9.21
Wind speed (m/s)	1.22	1.59	1.41	1.28	1.22	1.64	1.71	1.36	1.08	0.97	0.99	0.98

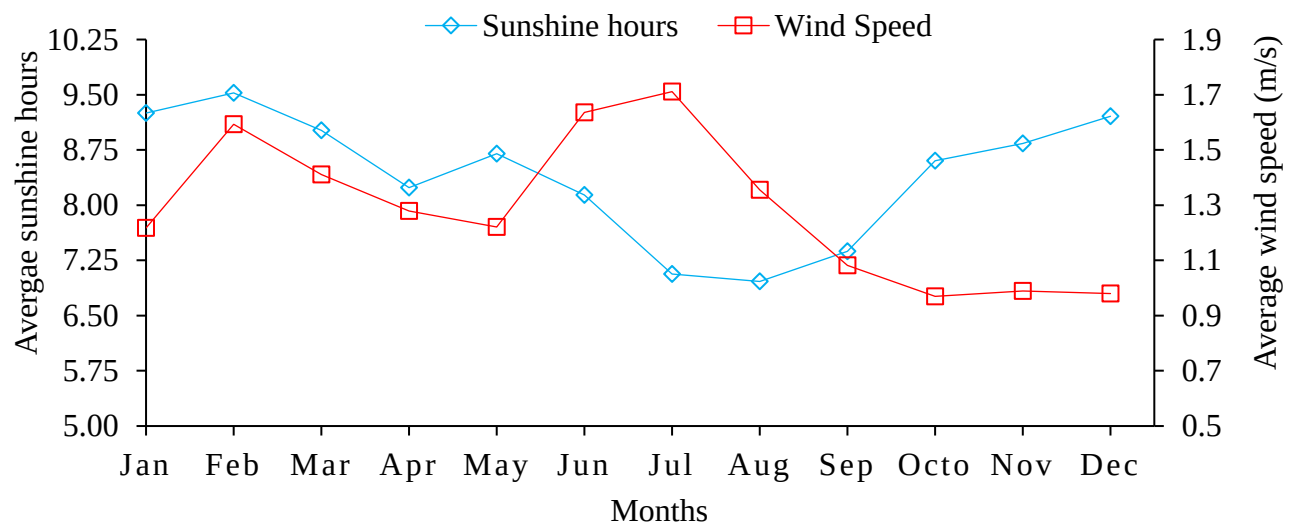


Figure 4.1: Monthly average sunshine duration for each month of Fantale

Figure 4.1 shows that the monthly average daily sunshine hours reach maximum and minimum on the month of February and August, respectively. This is due to the behavior of the season. Sunshine hour is maximum during winter in Ethiopia since most of the time it is clear sky. In summer season, there is a cloud and rain. So, the sunshine hour leads to the minimum value. The monthly average wind speed attains maximum and minimum on the month of July and October, respectively.

4.1.2.1 Preliminary Terminology and Sign Conventions

The major angles that describe the geometric relationship between the earth and the incoming solar radiation from the sun can be described in terms of several angles. Some of the angles are

Solar Time: It is the time dependent on the apparent angular movement of the sun across the sky with solar noon, the time the sun passes the observer's meridian. In all sun-angle correlations, solar time is employed. As a result, standard time must be converted to solar time using the equation of time, which accounts for changes in the earth's rate of rotation, and is given by equation (4.1a).

$$\text{Solar time} - \text{standard time} = 4(L_{st} - L_{loc}) + E \dots\dots\dots (4.1a)$$

Where, L_{st} - is the standard meridian for the local time zone; L_{loc} -is the longitude of the location.

The parameter E is the equation of time (min) and is given by equation (4.1b):

$$E = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B) \dots\dots\dots (4.1b)$$

$$B = (N - 81) \frac{360}{365} \dots\dots\dots (4.1c)$$

Where, N is day of the year which is counted starting from January 1, ($1 \leq N \leq 365$).

Latitude (ϕ): the angular location north or south of the equator, north positive: $-90^\circ \leq \phi \leq 90^\circ$.

Declination angle: The angular position of the sun at solar noon (i.e., when the sun is on the local meridian) with respect to the plane of the equator, north positive ($-23.45^\circ \leq \delta \leq 23.45^\circ$). The declination angle in degrees for any day of the year (N) can be found from the equation (4.2) (Bekele *et al.*, 2013).

$$\delta = 23.45 \sin \left[\frac{360}{365} \times (284 + N) \right] \dots\dots\dots (4.2)$$

Solar hour angle (ω_s): the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour (morning negative and afternoon positive) and cited from (Jayaprakash *et al.*, 2012). Here, LST is the local solar time.

$$\omega_s = 15^\circ \times (LST - 12) \dots\dots\dots (4.3)$$

Sunrise and sunset times and day length: The sun is said to rise and set when the solar altitude angle (α) is zero. The hour angle at sunset (ω_{ss}), can be found by (Bekele *et al.*, 2013): -

$$\omega_{ss} = \cos^{-1} (-\tan \delta \times \tan \phi) \dots\dots\dots (4.4a)$$

Meanwhile, the hour angle at local solar noon is zero, with each 15° of longitude equivalent to 1hr, the sunrise (ω_{sr}) and sunset (ω_{ss}) time in hours from local solar noon is then given as:

$$\text{Sunrise } (\omega_{sr}): \omega_{sr} = 12 - \frac{1}{15} \times \cos^{-1} (-\tan \delta \times \tan \phi) \dots\dots\dots (4.4b)$$

$$\text{Sunset } (\omega_{ss}): \omega_{ss} = 12 + \frac{1}{15} \times \cos^{-1}(-\tan \delta \times \tan \phi) \dots\dots\dots (4.4c)$$

The length of sun shine hours (N_s) are computed from: -

$$N_s = \frac{2}{15} \omega_{ss} \dots\dots\dots (4.4d)$$

Angle of incidence (θ): The angle formed between the beam radiation on a surface and the line normal to that surface is known as angle of incidence (Sebaili and Khallaf, 2020).

$$\cos \theta = \left[\begin{array}{l} \sin \delta \sin \phi \cos \beta - \sin \delta \cos \phi \sin \beta \cos \gamma + \cos \delta \cos \phi \cos \beta \cos \omega \\ + \cos \delta \sin \phi \sin \beta \cos \gamma \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega \end{array} \right] \dots\dots (4.5a)$$

$$\cos \theta = \cos \theta_z \cos \beta + \sin \theta_z \sin \beta \cos (\gamma_s - \gamma) \dots\dots\dots (4.5b)$$

$$\cos \theta = \cos \delta \cos (\phi - \beta) \cos \omega + \sin \delta \sin (\phi - \beta) \dots\dots\dots (4.5c)$$

Where: ϕ is the location latitude angle, γ is the surface azimuth angle, and β is the surface tilt angle. Additional angles are defined that describe the position of the sun in the sky.

Surface azimuth angle (γ): the deviation of the reflected on a horizontal plane of the perpendicular to the surface from the local meridian, with zero due east negative, west positive, and south; $-180^\circ \leq \gamma \leq 180^\circ$.

Zenith angle (θ_z): the angle formed between vertical and line to the sun, that is the angle at which beam radiation strikes a horizontal surface and is given by equation (4.6) (Altarawneh *et al.*, 2017):

$$\cos \theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \dots\dots\dots (4.6)$$

Solar azimuth angle (γ_s): the angular displacement of the beam radiation reflection on horizontal plane from the south. East of south and west of south shifts are negative and positive, respectively.

$$\gamma_s = \text{sign}(\omega) \left| \cos^{-1} \left(\frac{\cos \theta_z \sin \phi - \sin \delta}{\sin \theta_z \cos \phi} \right) \right| \dots\dots\dots (4.7)$$

Collector tilt (β): The tilt of a collector is the angle between the examined surface and the local horizontal. In most pyramid shape solar still, a tilt angle is approximately, $\beta = 30^\circ$ on horizontal this was the best angle according to (Altarawneh *et al.*, 2017). This tilt angle was selected to maximize the insolation received by the absorber and minimize reflection losses.

4.2 Extraterrestrial Daily Solar Radiation on a Horizontal Surface

The solar radiation (I_o) incident on a horizontal plane in the extraterrestrial region (outside the atmosphere) in W/m^2 can be obtained as follows (Ibrahim and Elshamarka, 2015):

$$I_0 = I_{ext} \times \cos \theta_z \dots\dots\dots (4.8a)$$

$$I_{ext} = I_{sc} \left(1 + 0.033 \cos \left(\frac{360n}{365} \right) \right) \dots\dots\dots (4.8b)$$

Where, $\cos \theta_z$ can be given by equation (4.6) and I_{sc} is the solar constant defined as the radiant solar flux received in the extraterrestrial region on a plane of unit area kept perpendicular to the solar radiation at the mean Sun Earth distance. The value of solar constant (I_{sc}) is 1367 W/m^2 .

At any point in time, the solar radiation incident on a horizontal plane outside of the atmosphere is the normal incident solar radiation as given by Klein relationship Equation (Bekele *et al.*, 2013):-

$$I_0 = I_{sc} \left(1 + 0.033 \cos \left(\frac{360n}{365} \right) \right) \times (\cos \phi \cos \delta \cos \omega + \sin \delta \sin \phi) \dots\dots\dots (4.8c)$$

The daily extraterrestrial solar radiation on a horizontal surface (H_o) can be determined by equation (4.9) in J/m^2 day during the period from sunrise to sunset (Bekele *et al.*, 2013):

$$H_o = \frac{24 \times 3600}{\pi} I_{sc} \left(1 + 0.033 \cos \left(\frac{360n}{365} \right) \right) \times \left(\cos \phi \cos \delta \sin \omega_s + \frac{\pi}{180} \omega_s \sin \delta \sin \phi \right) \dots\dots\dots (4.9)$$

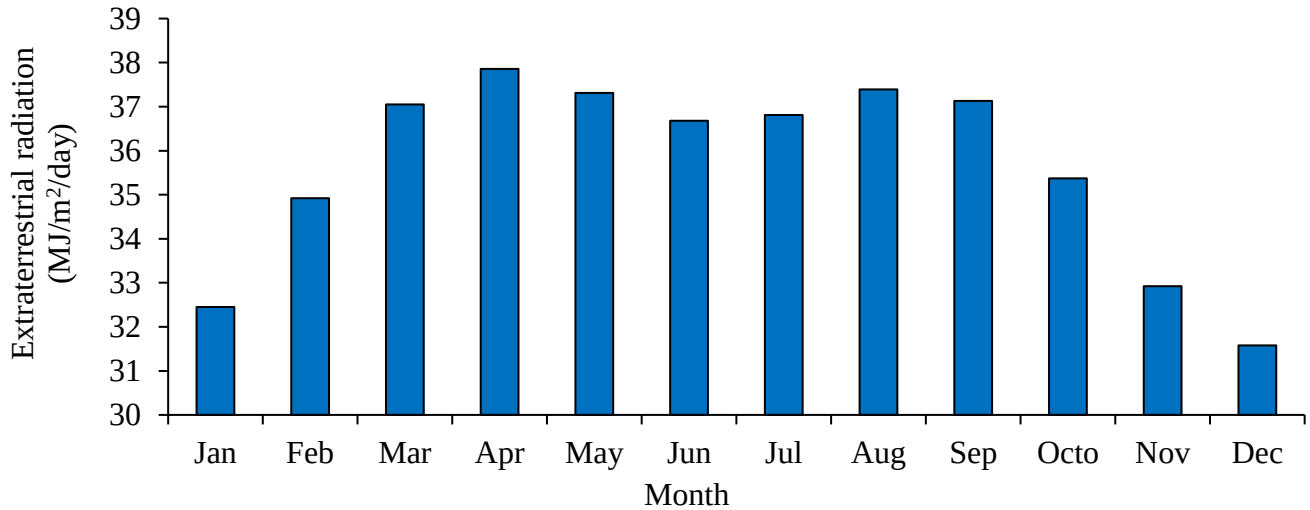


Figure 4.2: Monthly average daily extraterrestrial radiation on a horizontal surface

Where, n is average days of the month and ω_s = sunrise hour angle. The monthly average daily extraterrestrial radiation on a horizontal surface was shown in above Figure 4.2.

4.2.1 Estimation of Hourly Solar Radiation on a Horizontal Surfaces

4.2.1.1 Prediction of Monthly Average Daily Global Radiation on a Horizontal Surface

The first empirical correlation using the idea of employing sunshine hours for the estimation of global solar radiation was proposed by Angstrom. Angstrom equation is the simplest model for

estimating monthly average daily solar radiation on a horizontal surface (Bekele *et al.*, 2013) and can be estimated by equation (4.10a).

$$\frac{H}{H_0} = a_1 + b_1 \left(\frac{n_s}{N_s} \right) \dots\dots\dots (4.10a)$$

Where: H - Monthly average daily global solar radiation on horizontal surface.

H_0 - Monthly average daily extraterrestrial solar radiation on a horizontal surface (J/m^2)

n_s - Monthly average daily hours of bright sunshine (sunshine hour).

N_s - Monthly average of the maximum possible daily hours of bright sunshine.

The regression parameters a and b can be determined by equation (4.10b) and (4.10c):

$$a_1 = -0.110 + 0.235 \cos \phi + 0.323 \left(\frac{n_s}{N_s} \right) \dots\dots\dots (4.10b)$$

$$b_1 = 1.449 - 0.533 \cos \phi - 0.694 \left(\frac{n_s}{N_s} \right) \dots\dots\dots (4.10c)$$

The monthly average daily global radiation on a horizontal surface was shown in Figure 4.3.

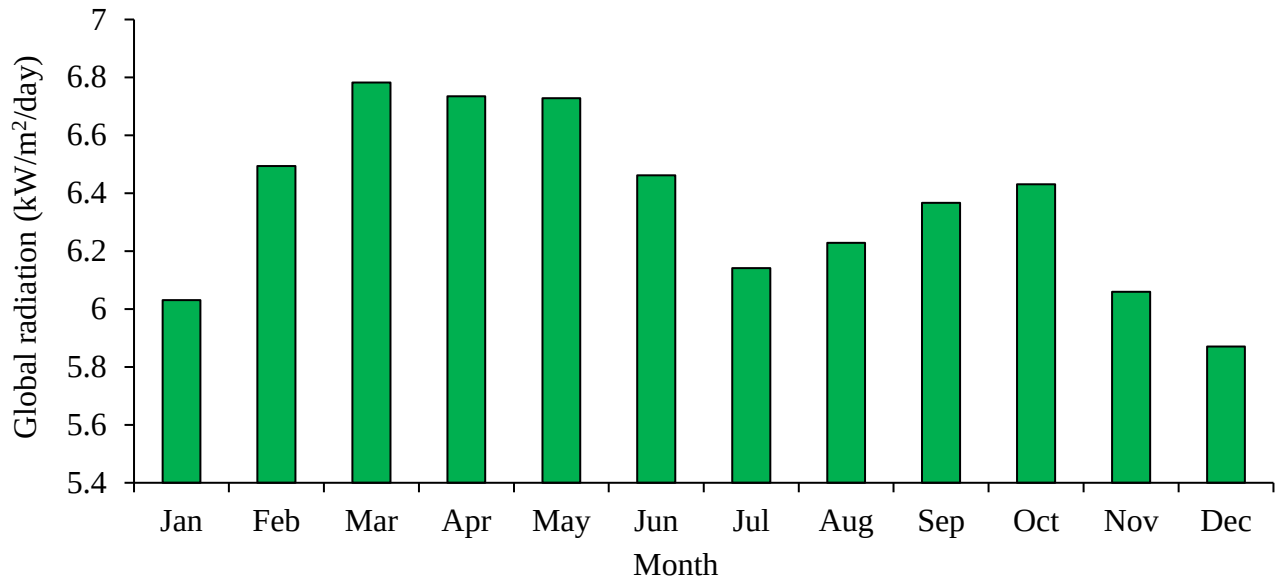


Figure 4.3: Monthly average daily global radiation on a horizontal surface

4.2.1.2 Prediction of Monthly Average Daily Diffuse Radiation on a Horizontal Surface

The monthly average daily diffuse radiation on a horizontal surface (H_d) can be determined from the monthly average daily global radiation on a horizontal surface and the number of bright sunshine hours (Bekele *et al.*, 2013). H_d can be determined by equation (4.11) and in MJ/m^2 day.

$$\frac{H_d}{H} = 0.931 - 0.814 \left(\frac{n_s}{N_s} \right) \dots\dots\dots (4.11)$$

The monthly average daily beam radiation (H_b) on a horizontal surface is the difference between the monthly average daily global and diffuse radiations (Mahian *et al.*, 2017).

$$H_b = H - H_d \dots\dots\dots (4.12)$$

The monthly average daily global, and diffuse radiation on a horizontal surface of Fantale and Adama city averaged for ten years of climatic condition was indicated in Figure 4.4.

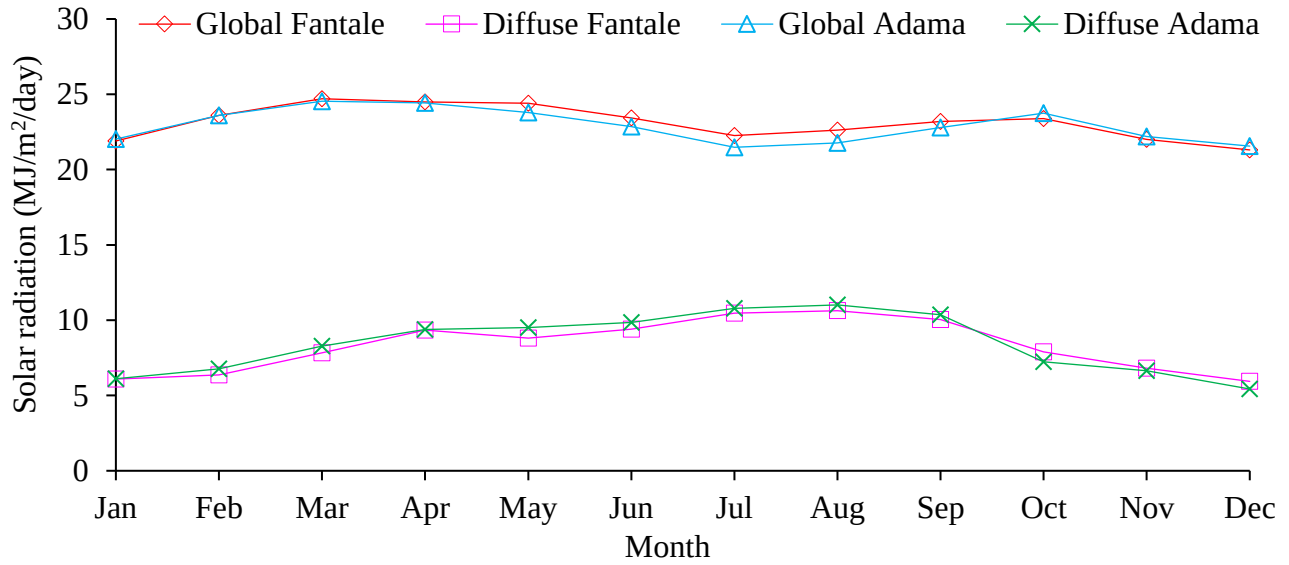


Figure 4.4: Monthly average daily global, diffuse and beam radiation on a horizontal surface

4.2.1.3 Prediction of Monthly Average Hourly Global Radiation on a Horizontal Surface

The monthly average hourly global radiation on a horizontal surface (I) can be determined from the monthly average daily global radiation on a horizontal surface (Bekele *et al.*, 2013). I can be determined by equation (4.13a) and in W/m^2 day.

$$\frac{I}{H} = \frac{\pi}{24} (a_2 + b_2 \cos \omega) \frac{\cos \omega - \cos \omega_s}{\sin \omega_s - \frac{\pi}{180} \omega_s \cos \omega_s} \dots\dots\dots (4.13a)$$

Where empirical constant a and b can be estimated by equation (4.13b) and (4.13c), respectively.

$$a_2 = 0.409 + 0.5016 \sin(\omega_s - 60) \dots\dots\dots (4.13b)$$

$$b_2 = 0.6609 - 0.4767 \sin(\omega_s - 60) \dots\dots\dots (4.13c)$$

Hourly variation of global radiation at each representative day of month for each of 24 hours in an hour interval is presented in Figure 4.5. As the graph shows global radiation intensity is detected from 6 AM up to 18 PM of the day (maximum at solar noon and minimum at sunset and sunrise).

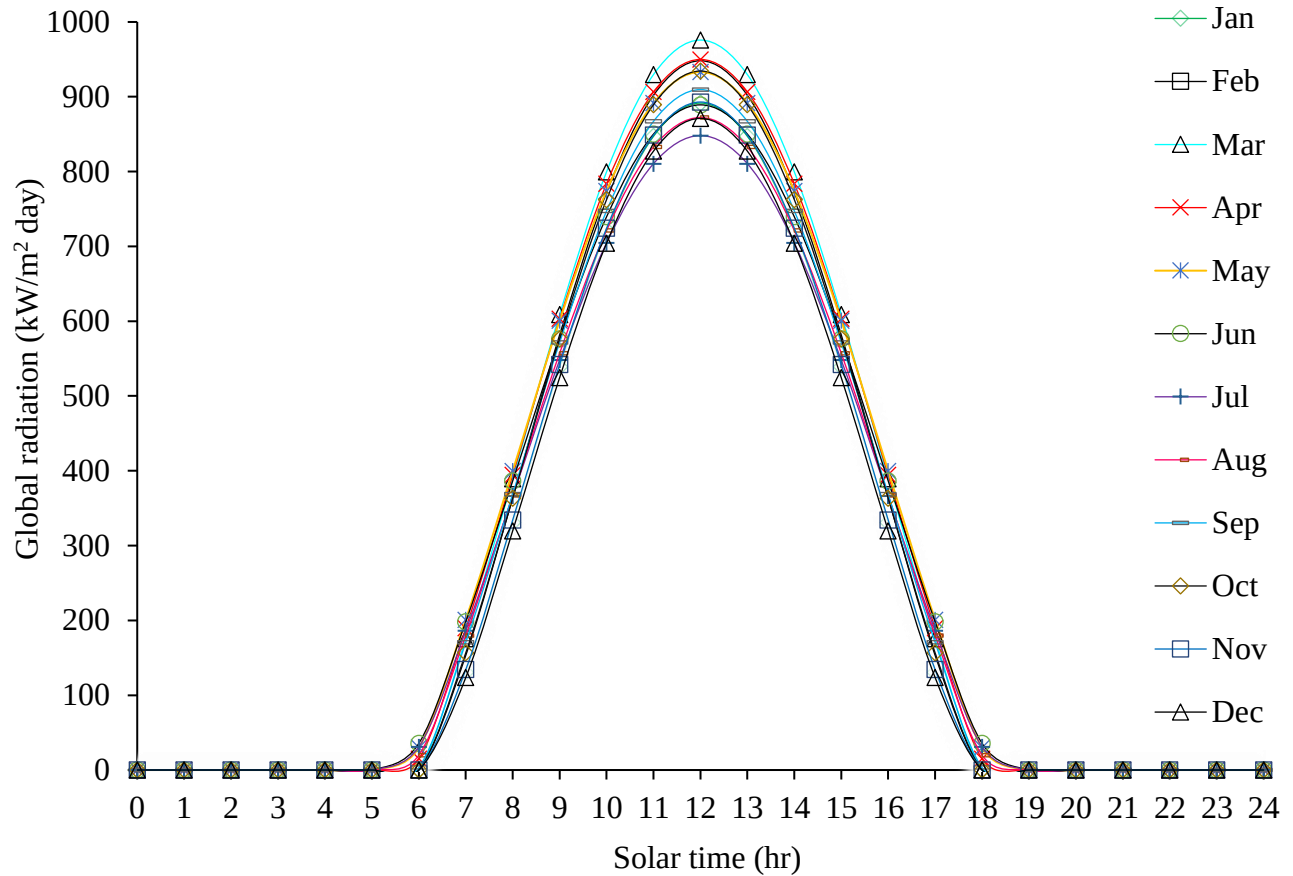


Figure 4.5: Monthly average hourly global solar radiation on a horizontal surface

4.2.1.4 Prediction of Monthly Average Hourly Diffuse Radiation on a Horizontal Surface

The monthly average hourly diffuse radiation on a horizontal surface (I_d) can be calculated from the knowledge of monthly average daily diffuse radiation on a horizontal surface (Bekele *et al.*, 2013). I_d can be estimated from the equation (4.14) and in W/m^2 day.

$$\frac{I_d}{H_d} = \frac{\pi}{24} \frac{\cos \omega - \cos \omega_s}{\sin \omega_s - \frac{\pi}{180} \omega_s \cos \omega_s} \dots\dots\dots (4.14)$$

The monthly average hourly beam radiation on a horizontal surface (I_b) is the difference between the monthly average hourly global and diffuse radiations. The direct (beam) component of the solar radiation on a horizontal surface is then obtained from equation (4.15):

$$I_b = I - I_d \dots\dots\dots(4.15)$$

4.2.2 Estimation of Total Incident Solar Radiation on a Tilted Surface

The amount of insolation on terrestrial surface at a given location for a given time depends on the orientation and slope of the surface. The incident solar radiation on an inclined surface (I_T) is the sum of the beam, diffuse and reflected solar radiation from various surfaces (from a horizontal surface and surrounding it) and can be estimated by equation (4.16a) (Mahian *et al.*, 2017).

$$I_T = I_b R_b + I_d \left(\frac{1 + \cos \beta}{2} \right) + (I_b + I_d) \rho \left(\frac{1 - \cos \beta}{2} \right) \dots\dots\dots(4.16a)$$

Where: I_T - Total hourly solar radiation on a tilted surface (W/m^2)

I_b - Hourly beam solar radiation (W/m^2)

I_d - Hourly diffuse solar radiation (W/m^2)

β - Surface slope angle and

ρ_g - reflectivity (0.2 for bare earth and 0.7 for snow)

Beam radiation factor (R_b) can be defined as the ratio of the incident beam radiation on a tilted surface to that on a horizontal surface.

$$R_b = \frac{I_{bT}}{I_{bM}} = \frac{I_b \cos \theta}{I_b \cos \theta_z} = \frac{\cos \theta}{\cos \theta_z} \dots\dots\dots(4.16b)$$

By substituting equation (4.16b) into (4.16a), solar radiation intensity can be calculated by using the equation (4.16c) (Katekar and Deshmukh, 2020):

$$I_t = I_b \cos \theta + I_d \cos \theta_z \left(\frac{1 + \cos \beta}{2} \right) + 0.2(I_b + I_d) \cos \theta_z \left(\frac{1 - \cos \beta}{2} \right) \dots\dots\dots(4.16c)$$

The total incident solar intensity on a surface tilted at an angle β can be expressed in terms of the global, beam, diffuse and the total reflected radiation to the tilted surface can be shown in Figure 4.6 for Fantale.

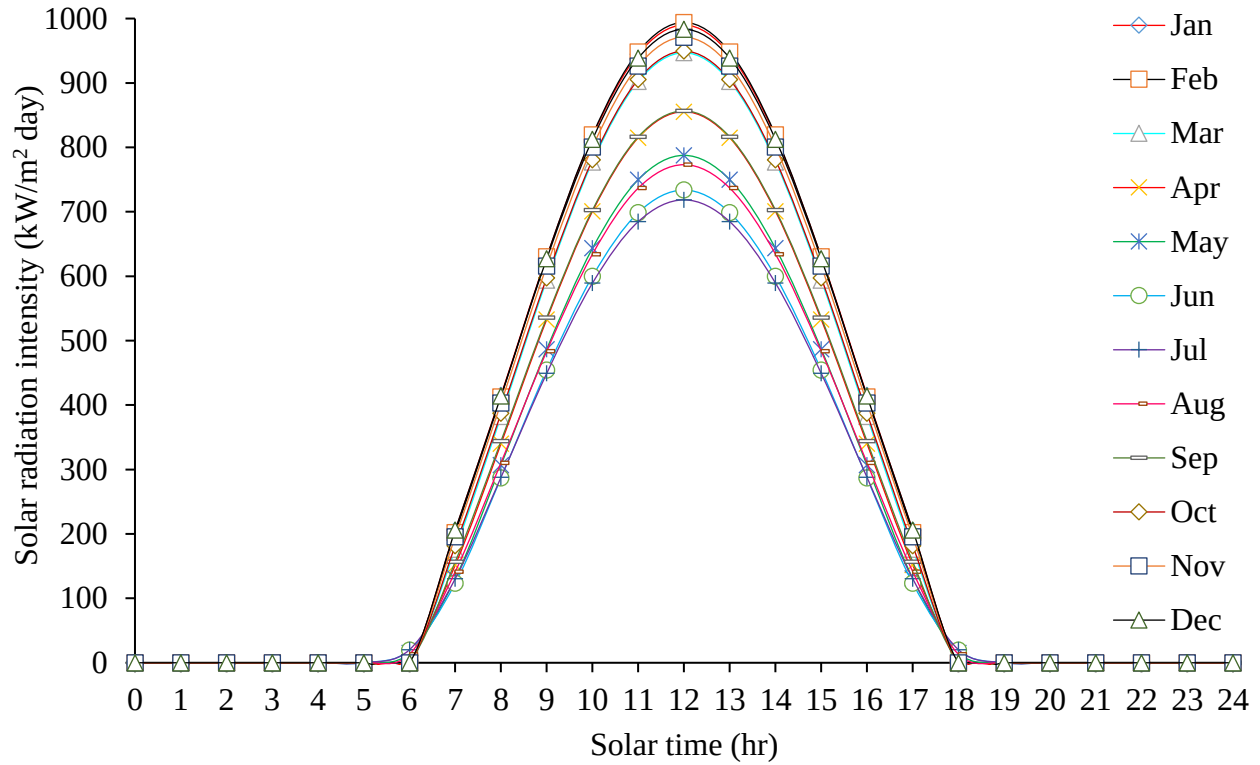


Figure 4.6: Monthly average hourly total incident solar radiation on a tilted surface

4.3 Fantale Metrological Temperature Data

Fantale is characterized by a climatic condition of the hot region and it has a maximum of solar radiation intensity. Ten years average climatic conditions of Fantale were taken to evaluate the average monthly temperature. The collected monthly average temperature data and its average values was shown in Table 4.2 and Figure 4.8 for each month.

Table 4.2: Monthly average temperature annual climatic conditions of Fantale

Year	Months in years Temperature (°C)											
2012-21	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T(max.)	31.99	33.79	36.45	36.34	36.54	37.15	33.69	32.99	33.87	33.11	32.98	31.6
Average	22.4	24.8	27.54	28.31	28.19	29.46	27.14	26.66	26.78	25.6	24.2	22.15
T(min.)	12.81	15.8	18.63	20.27	19.84	21.77	20.6	20.33	19.7	17.08	15.42	12.71

Figure 4.7 shows the monthly average maximum and minimum temperatures of Fantale climatic conditions. The monthly average ambient temperature of Fantale ranges between 12.71 °C (December) and 37.15 °C (June).

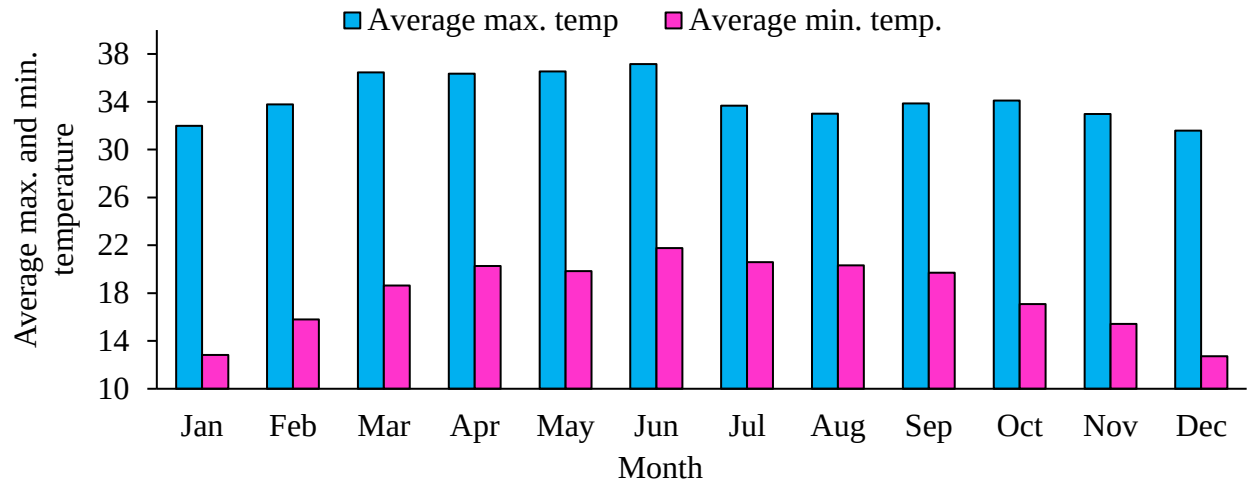


Figure 4.7: Monthly average maximum and minimum temperatures of Fantale

4.3.1 Estimation of Hourly Variation of Ambient Temperature

There are many methods of calculating variation of daylight of ambient temperature. Among them, the hourly variance of daily minimum and daily maximum temperatures can be estimated using an exponential sine model was selected. The method was proposed by Parton and Logan according to (Mavromatidis *et al.*, 2012). This model shows a diurnal cycle associated with a sine function during the day and the exponential function at nighttime. The model assumes that the highest temperatures will occur during the day before sunset, while the lowest will occur in the early morning. The mathematical description was stated as follows:

For daylight hours and night time hours can be found by equation (4.17a) and (4.17b), respectively.

$$T(H) = (T_{\max} - T_{\min}) \sin\left(\frac{\pi \times m}{y + 2a}\right) + T_{\min} \dots\dots\dots (4.17a)$$

$$T(H) = T_{\min} + (T_{\text{sunset}} - T_{\min}) \exp\left(\frac{-b \times n}{z}\right) \dots\dots\dots (4.17b)$$

Where: T (H) = Temperature at any hour of the day or night period determined from m and n (°C),

m = Number of hours between time at T_{min} and sunset (h)

n = Number of hours from sunset to the time of T_{min} (h)

T_{max} and T_{min} is the mean daily maximum and minimum temperature (°C), respectively. y is day length (h), z is night length (h), T_{sunset} is temperature at sunset (°C), a is lag coefficient for T_{max} = 1.80(h), b is night time temperature coefficient = 2.2 (h).

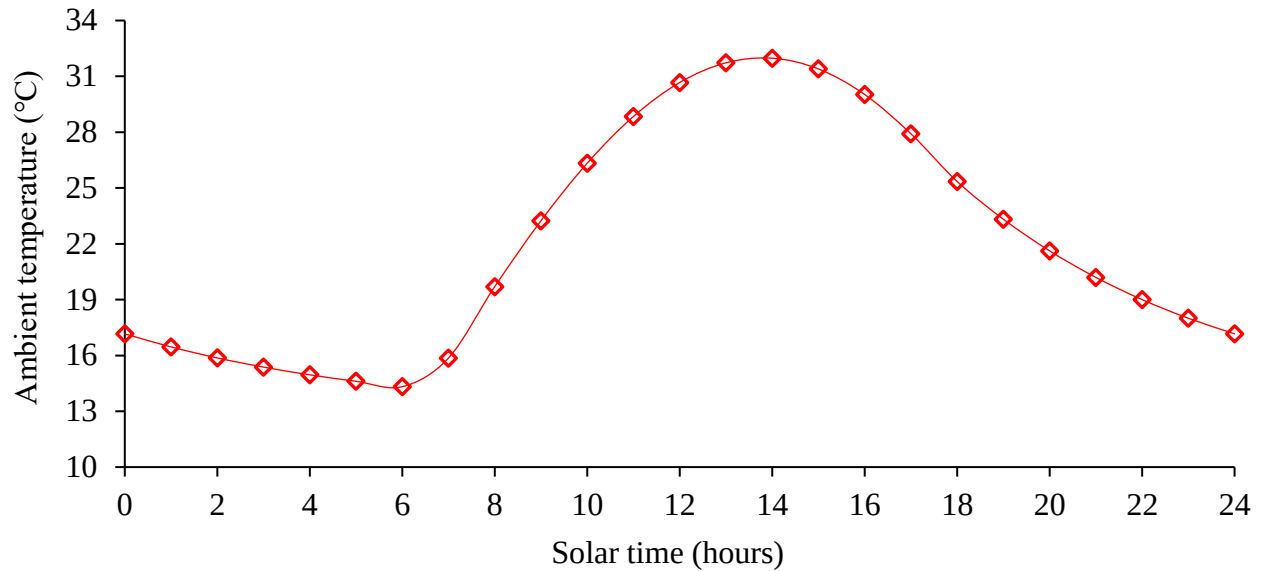


Figure 4.8: Result of average variations of ambient temperature of Fantale

4.4 Material Selection of the Solar Still Components

The performance of a solar still depends on the design parameters. It is a necessity to consider various techniques to minimize heat losses, maximize energy absorption and increase evaporation and condensation rates, thereby maximizing distillate production. Important aspects to consider are the material used, thickness, and strength. This section explains the considerations and choices made for the design of the solar still.

4.4.1 Basin Liner

The basin which contains the solar still is a major component to design for a good performance of the solar still. Several materials were considered for use as the basin material such as aluminium, stainless steel, galvanized steel, and others are used. The selected material should be able to absorb most of the solar radiation, should be durable, watertight, easy to clean and be able to withstand temperatures up to about 100. With its high strength, easy to clean surface due to the coating and relatively low cost, galvanized steel would be one of the most both economical and technically viable materials to be used for solar still basin. Galvanized steel was selected for this study.

4.4.2 Transparent Cover

Glass covers were designed to receive solar radiation from all direction to maximize the collected solar power. Glass cover is preferred in solar still due to high transmittance solar radiation, opacity for heat energy, protection from the scraped area, high strength for an extended duration, the great

wet capacity of water, and general accessibility. The surface glass covers are preferred opted compared to plastic material. The glass covers used were similar to the ordinary window glass of 3 mm thickness with an average emissivity of 0.88.

4.4.3 Insulation

Another essential material used in solar still is insulation. The low thermal conductivity of insulating material can survive high temperatures. Sufficient quality of insulation can be utilized as foot protection. Insulation material is selected based on low thermal conductivity and local availability. Insulation materials similar to fiberglass, rock wood, polyurethane, polystyrene, and straw may be used but require some care. Protection ought to stay dry as even a stick opening hole in the liner can degrade the property of the protection. To reduce heat loss from the bottom and side walls of the solar still, glass wool is designated with a thermal conductivity of 0.032 W/m K were utilized (Altarawneh *et al.*, 2017).

4.4.4 Sealant Material

One of the most essential components is a sealant material used to seal in a solar still. A portion of the sealant materials that can be utilized are tapes, tars, putty, silicon sealant and so far. Sealant selection should be versatile at low and large temperatures. To avoid vapor leakage, the glass cover was sealed with silicone rubber. Silicone rubber beading with 4 mm thickness was opted.

The list of materials used in this present study and their properties are depicted in Table 4.3.

Table 4.3: Summary of the materials components of the solar still considered

Component	Material(s)	Properties and comments
Basin	Galvanized steel	▪ High radiation absorptivity ▪ High thermal conductivity and stable to corrosion
Transparent cover	Glass	▪ Low water absorbance ▪ Transparent to short wave radiation ▪ High thermal conductivity ▪ Can withstand the effect of weather, wind.
Insulator	Glass wool and wood	▪ Low thermal conductivity and radiation of heat ▪ Very cheap and effective for insulation
Sealant material	Silicone rubber	▪ Versatile at low and large temperatures

4.5 Daily Requirements of Drinking Water

The system is being designed to fulfill the daily requirements of drinking water of a rural family. It is important to find the quantity of water that is required and subsequently the amount of heat energy required to evaporate the required quantity of water. Review and analysis show that bare minimum water requirement for a person is 2 liters per day. Considering a family of 5, a system needs to be designed to evaporate 10 liters of water. Further, considering that solar energy is available for nearly 7 hours a day. The system should be capable of evaporating the required quantity of water in 7 hours. Energy needed to evaporate 10 kg of water in 7 hours of time is calculated as follows.

4.5.1 Energy Requirement

Assume the yield of the conventional solar still was 5 liters/day (Narayanan *et al.*, 2020). Amount of latent heat required to change liquid state of water in to vapor state is given by equation (4.18).

$$Q_{latent} = m h_{fg} \dots\dots\dots(4.18)$$

Heat energy rate required to evaporate the quantity of water is calculated using equation (4.19).

$$Q = \frac{m h_{fg}}{\text{time}} \dots\dots\dots(4.19)$$

Where Q is the amount of energy rate required, m is mass of water, and h_{fg} is latent heat of water (2257 kJ/kg).

Energy needed to evaporate 5 kg of water in 7 hours of time is calculated using equation (4.19).

$$Q = \frac{5 \times 2257 \times 10^3}{7 \times 3600} = 447.82 \text{ W} \dots\dots\dots(4.20)$$

The above equation shows that the heat energy utilized at the absorber depends upon the solar radiations, area of glass cover and transmittivity of material. The intensity of radiations depends on climatic conditions and varies from place to place. Hence design of the absorber is based on transmittivity of material and area of the glass cover. The size of the absorber should be such that it generates 447.82 Watts of energy. If the values of intensity of radiations and transmittivity of material are found, then the area of the absorber can be calculated.

4.5.2 Area of Absorber Plate

The net solar energy falling on the surface of absorber plate, Q_s in W, is given by equation (4.21).

$$Q_s = I(t) \times A_p \dots\dots\dots(4.21)$$

Where, $I(t)$ is the total solar radiation intensity in W/m^2 , and A_p is the area of absorber plate in m^2 .

Further, net heat energy leaving the glass surface, Q_L is given by equation (4.22).

$$Q_L = Q_s \times \tau_g \dots\dots\dots(4.22)$$

Where, τ_g is the transmittivity of the glass (88%). The net heat energy available, Q_n at the surface of absorber is calculated by using equation (4.23a).

$$Q_n = I(t) \times A_p \times \tau_g \dots\dots\dots(4.23a)$$

The average value of solar radiation intensity, $I(t)$ for Fantale's village was analyzed from Ethiopia metrology agency and used for further calculations. Yearly solar radiation intensity of the region reaches up to $6.6 \text{ kWh}/m^2$ day, but taking the lowest $4 \text{ kWh}/m^2$ day, (to make an operational during the lowest solar radiation). Substituting, the lowest value of $I(t)$ in the equation (4.23a),

$$Q_n = \frac{4 \times 10^3 \times A_p \times 0.88}{7} = 502.9 A_p \dots\dots\dots(4.23b)$$

Area of absorber plate is calculated by equating equation (4.20) and (4.23b),

$$A_p = \frac{447.82}{502.9} = 0.9 \cong 1 m^2 \dots\dots\dots(4.23c)$$

Since the base of the pyramidal shape is square, thus its length and width are equal. The length and width of the basin is equal to 1 m.

4.5.3 Area of Glass Cover

In most pyramid shape solar still, a tilt angle is approximately, $\beta = 30^\circ$ on horizontal, this was recommended angle according to (Altarawneh *et al.*, 2017). From the trigonometric relations,

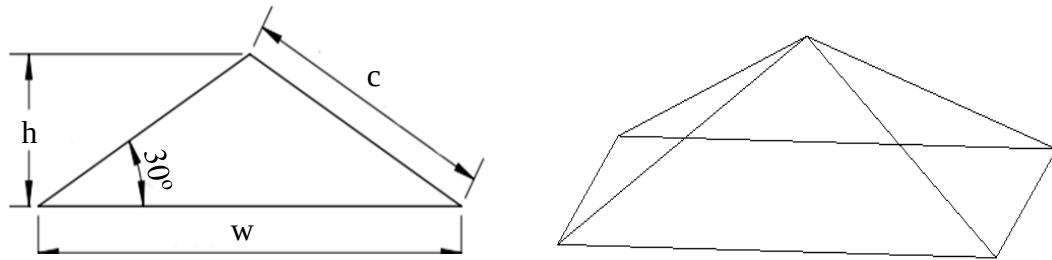


Figure 4.9: A schematic view of square pyramidal shape

$$\cos 30 = \frac{0.5 \times w}{c} \Rightarrow c = \frac{0.5 \times w}{\cos 30} = \frac{0.5 \times w}{0.866} = 0.577 w \cong 0.6 w \dots\dots\dots (4.24c)$$

$$\sin 30 = \frac{h}{c} \Rightarrow h = \sin 30 \times c = 0.5 \times 0.6 w = 0.3 w \dots\dots\dots (4.24d)$$

Area of square pyramidal shape is calculated as follows

$$A_g = \text{Area of the base} + \text{Area of each phase} = w \times l + (w \times h) \times 4 \dots\dots\dots (4.24e)$$

Area of glass cover is calculated as follows,

$$A_g = l \times w + (w \times 0.3 \times w) \times 4 = 1 \times 1 + (1 \times 0.3 \times 1) \times 4 = 2.2 m^2 \dots\dots\dots (4.24f)$$

$$h = 0.3 \times 1 = 0.3 m, \quad c = 0.6 \times 1 = 0.6 m \quad \text{and} \quad l = w = 1 m \dots\dots\dots (4.24g)$$

The above equation shows that to generate 447.82 Watts of energy, the area of glass cover and absorber plate should be 2.2 m² and 1 m², respectively. Hence, to generate 10 liters of freshwater for a family of five members, two such a system needs to be designed and fabricated.

4.6 Design of a Solar Still

The investigations have been performed on a pyramid solar still with the aim of showing the influences of a unique combination of impactful modifications such as v-corrugated absorber, nano-coated absorber surface, nano-embodied PCM and reflective mirrors on the accumulated output of pyramid solar stills. The analyzes were carried out with two distinct pyramid solar still: one is a modified pyramid solar still (MPSS) with a unique combination of effective modifications, and the other is a conventional pyramid solar still (CPSS) that serves as the reference case.

4.6.1 Design Details of a Conventional Pyramid Solar Still (CPSS)

Pyramid solar still of area 1 m x 1 m was designed. The still has the capacity to store the water up to a height of 0.05 m. Top of the system was covered by a 4 mm transparent glass pyramid cover with a height of 0.30 m at the middle. It is air tightened using the cushion supports at the interface between the top cover and the sides of sliding support for uniform landing. The bottom and side of the still was insulated with glass wool.

The schematic view of CPSS was shown in Figure 4.10. The detail specification of different parts of the CPSS is shown as follows.

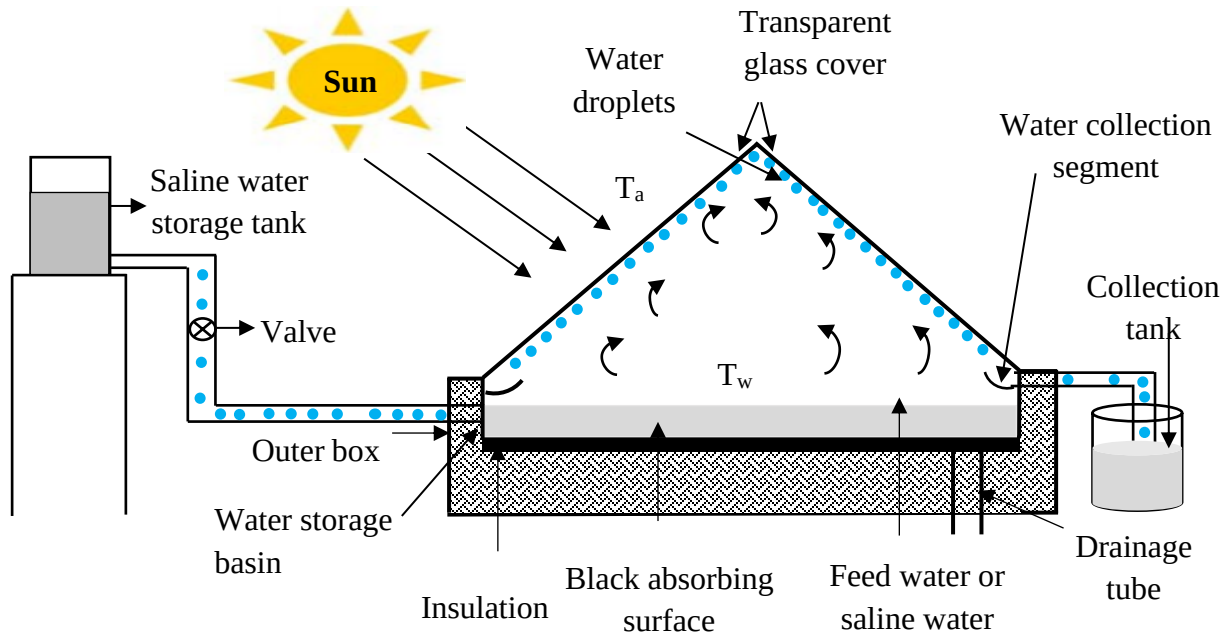


Figure 4.10: A schematic view of conventional pyramid solar still

4.6.1.1 Water Storage Basin

The water storage basin of the still is constructed from galvanized steel with a dimension 1 m x 1 m x 0.15 m. Bottom and sides of the basin are painted with black paint for good absorption of solar radiation. Pipe and valve are used for pouring water into the still and it is fixed at the height of 0.125 m on the side of the still. Another pipe is placed at a height of 0.125 m adjacent to the inlet pipe for the inlet of thermocouples into the still to measure the temperature inside the still.

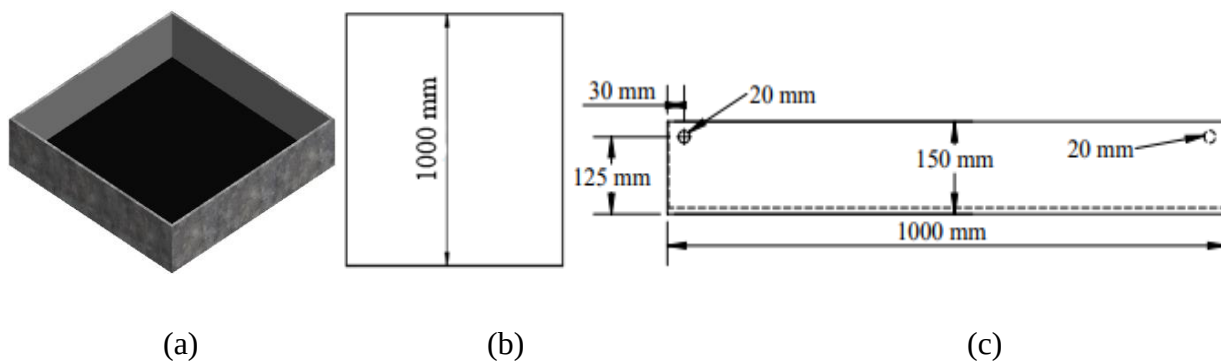


Figure 4.11: Water storage basin (a) 3D Model (b) Top view (c) Front view

4.6.1.2 Water Collection Segment

Water collection segment of this proposed system is bent in the required “U” shape of dimension 1 m x 0.03 m x 0.03 m and is fixed at the inner sidewall of still at the height of 0.14 m. Distilled

water outlet provision from the water collecting segment is made at diagonally opposite sides by joining two sides collection together. Water collection pipes located on all sides of the still. However, water outflow pipes will only be on the diagonally opposite sides. Chemical adhesives are used to seal the fine gap between the water storage basin and the water collection segment, to prevent any water leakage between the water collection segment and the water storage segment. Strips are provided just above the water collection segment at a distance of 0.005 m from it for the uniform landing of top cover and also to effectively collect the condensed distilled water.

4.6.1.3 Inlet of the Still and Water Circulation Provision

Water inlet provision is given by fixing the one pipe of height 0.125 m on the rear side of the still. Water is poured to the basin through this inlet by using the funnel and tubing set up. A pair of pipes are fixed on the bottom of the base of the still at diagonally opposite to each other for the circulation of water. These pipes are fused exactly at the corners of diagonal end of the basin.

4.6.1.4 Outer box

The outside of still with a dimension of 1.1 m x 1.1 m x 0.20 m is built of 2 mm thick wood. Frame are placed at the base of the still for uniform landing in the ground. The inlet, outlet, distilled water collecting pipes, and waste water flow pipes are all marked with appropriate strips in the exterior cover. For suitable handling of the still, handles are supplied on opposing sides of the outer box.

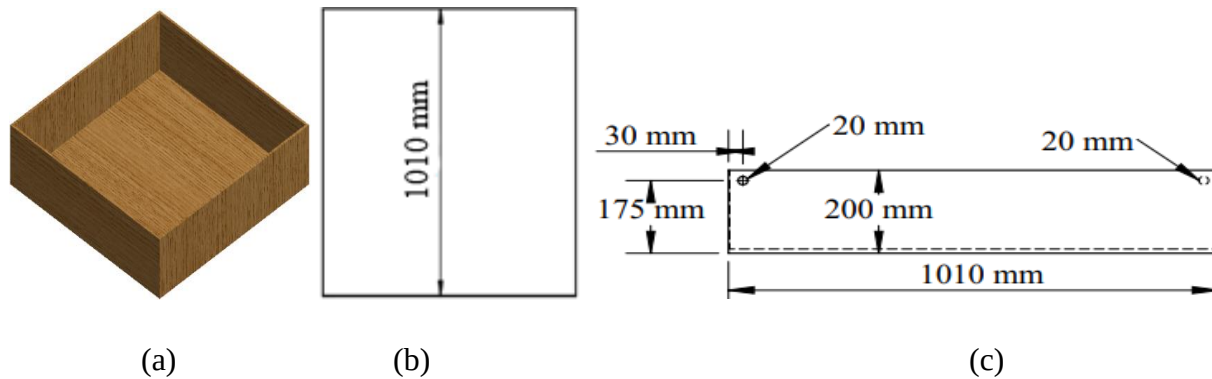


Figure 4.12: Outer box storage basin (a) 3D Model (b) Top view (c) Front view

4.6.1.5 Square Pyramid Top Cover

Square pyramidal top cover of area 1 m x 1 m is designed using 4 mm transparent glass material. It is designed by joining the four side by silicon chemical adhesive. The top cover is placed over

the strip provision provided at all sides for uniform resting over the water collection segment. The distance between the top of the pyramid to the center of surface area is 0.3 m.

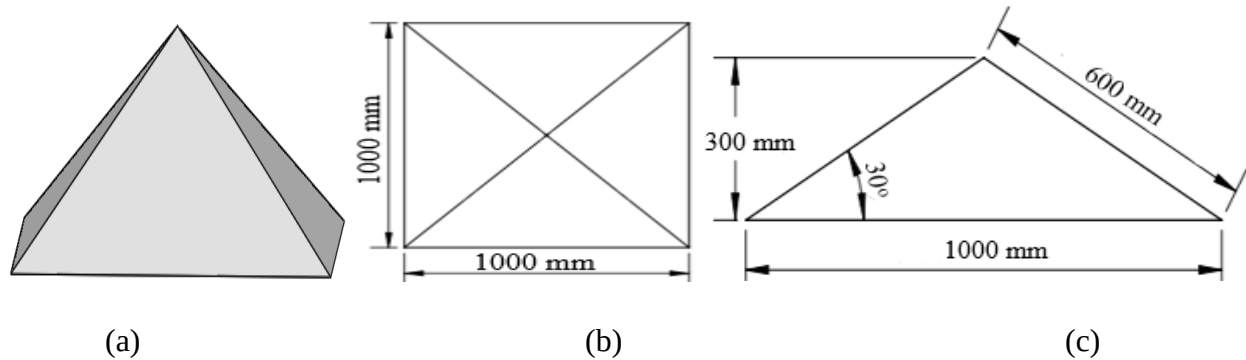


Figure 4.13: Square pyramidal shape (a) 3D Model (b) Top view (c) Front view

4.6.1.6 Fixation of Top Cover

Small pieces of steel strips are welded with a dimensions of 0.01 m x 0.01 m and at the height of 0.005 m from the top surface on the inner side of the still basin. So that the top glass pyramid cover lands uniformly and the distilled water are collected freely in the water collection segment. Finally, this top cover is bolted air tightly using the cushion supports at the interface between the top cover and the sides of sliding support for uniform landing.

4.6.1.7 Insulation

The bottom and side of the basin is insulated with the glass wool and wood. This insulation is made to reduce the conduction heat loss through the base and sides of the solar still.

4.6.1.8 Valves and Pipes

Ball valves and pipes are used at the various places in this setup. Saline water inlet and outlet with a diameter of 20 mm and for drainage 35 mm is used. Three total number of valves used. Galvanized steel pipes were opted for saline water supply pipes and suggested filtration transport.

4.6.1.9 Support Materials

The stand is required to support the solar still from the floor with a dimension of 1.20 m x 1.20 m x 0.7 m. Mild steel rectangular and flat plate with 4 mm thick was opted.

4.6.2 Design Details of a Modified Pyramid Solar Still (MPSS)

Regarding the MPSS, it has the same dimensions as the CPSS. However, to improve the performance of the CPSS four proposed modifications have been applied through an experimental and theoretical investigation. The cross-sectional view of MPSS was shown in Figure 4.14.

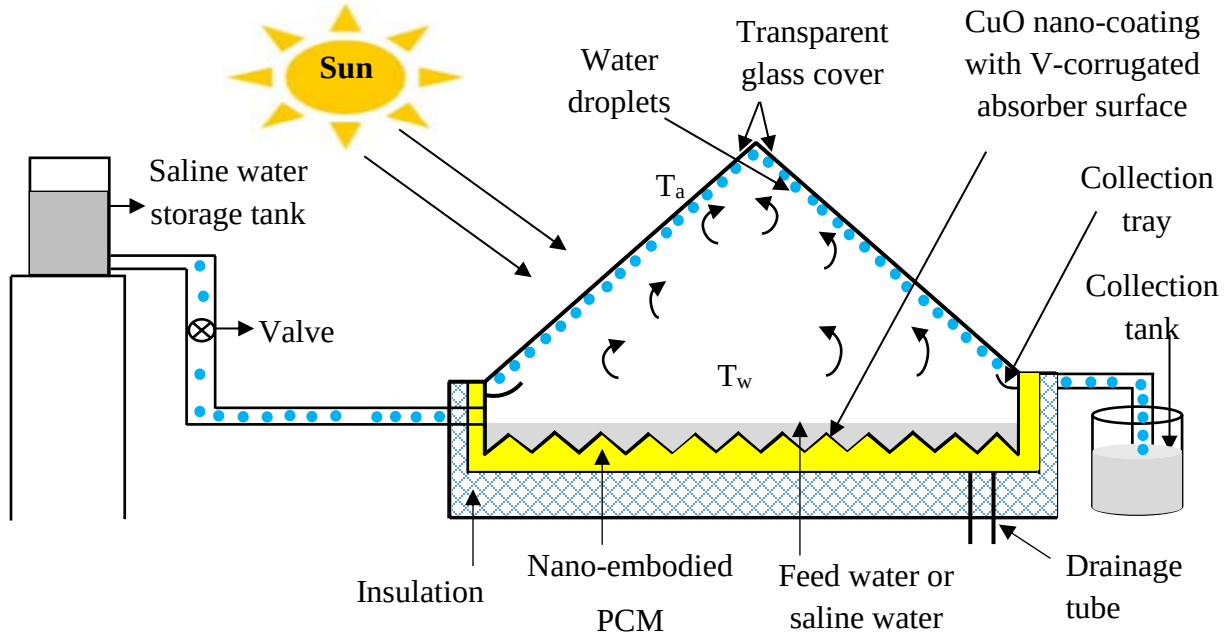


Figure 4.14: A Schematic diagram of modified pyramid solar still

The design details of proposed solar still with its modifications are specified as follows.

4.6.2.1 V-corrugated Absorber

The first modification to this CPSS was v-corrugated absorber, which is utilized to increase the evaporation surface area. The MPSS basins have the same dimensions as the CPSS, but also has the inclusion of a 1 m x 1 m v-corrugated square basin with a height of 0.05 m.

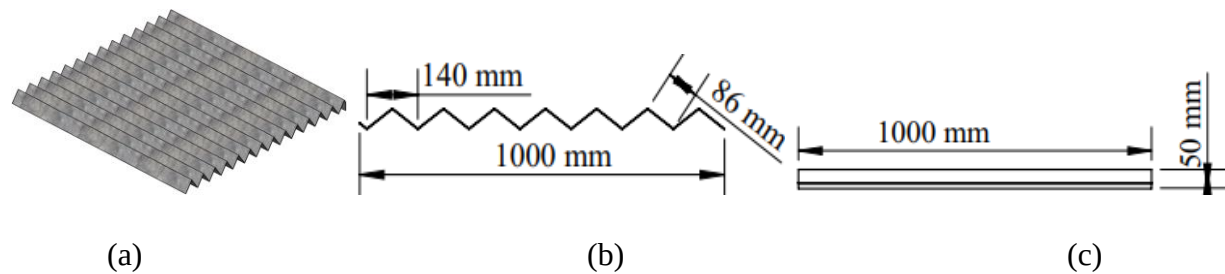


Figure 4.15: V-corrugated absorber basin (a) 3D Model (b) Front view (c) Top view

The square basin is constructed from galvanized iron sheet in the shape of a v-corrugated basin. This square v-corrugated basin is placed in the pyramid distiller's main square area. Use of v-corrugated absorber to increase the surface area of evaporation subjected to solar radiation.

4.6.2.2 Nano-coated Absorber Surface

Inclusion of NPs mixed with black paint on the v-corrugated absorbers utilized to maximize the rate of solar insolation and absorptivity, it represents the second modification in this present study.

4.6.2.2.1 Selection of Nanoparticles

From the various types of nanoparticles, copper oxide nanoparticle (CuO NP) was selected based on their thermal conductivity and cost affordable, according to (Elango *et al.*, 2015). When compared to carbon nanotubes and other nano-powders used to produce nanofluids, CuO NP were moderate in cost and also available in the local market. Even the thermal conductivity of some nano-powders is high they are unable to use because of their high cost.

4.6.2.2.2 Characterization of CuO Nanofluid

X-ray diffraction studies (XRD) is an easy tool to determine the size and the shape of the unit cell for any compound. Diffraction pattern gives info on translational symmetry - size and shape of the unit cell from peak positions and information on electron density inside the unit cell, namely where the atoms are located from peak intensities. From this study, considering the peak at degrees, average particle size has been estimated by using Debye-Scherrer formula (Ahamed *et al.*, 2014).

$$D = \frac{0.9 \lambda}{\beta \cos \theta} \dots\dots\dots (4.25a)$$

Where ' λ ' is wave length of X-ray ($\lambda = 0.1541$ nm), ' β ' is full width at half maximum, ' θ ' is the diffraction angle and ' D ' is particle diameter size.

Calculation of d-Spacing: The value of d (interplanar spacing between the atoms) was calculated using Bragg's Law:

$$d = \frac{\lambda}{2 \sin \theta} \dots\dots\dots (4.25b)$$

The diffraction peaks of nanoparticle were important to estimate the average particle size. The XRD test was conducted in Material Science and Engineering department, ASTU. The nanoparticle size of copper oxide can be summarized as follows and was shown in Table 4.4.

Table 4.4: Nanoparticle size of copper oxide

2θ of the intense peak (deg)	θ of the intense peak (deg)	FWHM of Intense peak (β) in radians	Size of the particle (D) Nm	d-spacing nm
35.5487	17.7744	0.011552	12.607	0.252
38.7632	19.3816	0.010629	13.832	0.232
48.7199	24.3600	0.012411	12.267	0.187

The particle sizes of XRD result vary in the range between of 12-14 nm is almost similar with that of (Suresh and Kalaiselvam, 2017; Ahamed *et al.*, 2014) in which as stated in literature.

4.6.2.2.3 Estimation of Nanoparticle Volume Concentration

The amount of nanoparticle required for preparation of nanofluid is calculated using the law of mixture formula. Particle volume fraction is a parameter that is investigated in almost all of the experimental studies and the results are usually in agreement qualitatively. Most of the researcher's report increasing thermal conductivity with increasing particle volume fraction and the relation found is usually linear. Percentage of volume concentration can be found as equation (4.26):

$$\phi = \left(\frac{m_{NP}}{m_{NP} + m_{bf}} \right) \times 100 = \left(\frac{\frac{W_{CuO}}{\rho_{CuO}}}{\frac{W_{CuO}}{\rho_{CuO}} + \frac{W_{bf}}{\rho_{bf}}} \right) \times 100 \dots\dots\dots (4.26)$$

where φ is the percentage of weight concentration

4.6.2.2.4 Thermophysical Properties of CuO Nanoparticles

Nanofluids have plentiful specific features compared to the pure water, for example, large insolation absorptivity, large thermal conductivity, large surface area, and low specific heat as well, which improve the freshwater production.

The mass of nanoparticle is measured and selected as per the total volume of the base fluid. The measured nano-powders are then added to the base fluid to form the colloidal homogenous solution. The fluid is then treated as the nanofluid so as to estimate the heat carrying capacity. In order to estimate the heat transfer improvement by the nanofluid, the various thermo-physical properties such as thermal conductivity, specific heat, density, viscosity of the nanofluid must be calculated and were summarized in Appendix B.

Various correlations were offered provided by the different researchers for estimating the physical properties of the nanofluid at the different concentration of nanoparticle with base fluid. The correlations are in terms of the physical properties of solid nanoparticle (copper oxide) and the base fluid. So, the properties of the nano-powders and the base fluid must be available independently, to assess the net effective properties of the nanofluid. The thermophysical properties of CuO nanoparticles are shown in Table 4.5 (Abdelgaied *et al.*, 2022).

Table 4.5: Thermophysical properties of CuO nanoparticles

Chemical composition	Density	Thermal conductivity	Specific heat	Size
CuO	6320 kg/m ³	76.5 W/m K	42.36 J/mol K	12-14 nm

The nanofluids thermophysical properties can be defined as functions of the nanoparticles and base fluid. The main thermophysical properties of nanofluids are given by the equations as follows (Sharshir *et al.*, 2020):

- Density of nanofluids (ρ_{nf}) is given by

$$\rho_{nf} = \left(\frac{\varphi}{100} \right) \rho_{np} + \left(1 - \frac{\varphi}{100} \right) \rho_{bf} \dots\dots\dots (4.27)$$

- Specific heat of nanofluids (C_{nf}) is given by

$$C_{nf} = \frac{(\varphi / 100) \rho_{np} C_{np} + (1 - (\varphi / 100)) \rho_{bf} C_{bf}}{\rho_{nf}} \dots\dots\dots (4.28)$$

- Thermal conductivity of nanofluids (K_{nf}) is given by

$$K_{nf} = K_{bf} \frac{K_p + (n-1) K_{bf} - (n-1) \varphi (K_{bf} - K_{np})}{K_p + (n-1) K_{bf} + \varphi (K_{bf} - K_{np})} \dots\dots\dots (4.29)$$

Mass of base fluid taken was half of kilograms of black ink paint.

Table 4.6: The value of volume concentration that used on the experiment

Weight of Nanoparticle in (grams)	Volume of concentration % ($\emptyset$)	Thermal conductivity (k_{eff}) (W/m K)	Density (kg/m ³)	Specific heat capacity (J/kg K)	Viscosity (μ_{eff}) ($N - S / m^2$)
38.62	1	0.1380	878.76	2206.51	0.0146
78.02	2	0.1422	933.52	2088.68	0.0149
118.24	3	0.1464	988.28	1983.92	0.0153

Coating the v-corrugated absorber with a mixture of black paint and CuO nanoparticle is the best way to use nanoparticle in solar still instead of releasing in water. This consequently raise the absorptivity of sun's radiation and improve the total heat transfer coefficient.

4.6.2.3 Nano-enhanced PCM

Employing PCM with CuO nanoparticle beneath the v-corrugated basin, is termed as the third modification in this present study. The design includes selection of a storage material and sizing of heat storage unit.

4.6.2.3.1 Selection of Storage Material

The main criteria for the selection of PCM should be done with reference to the water temperature and melting point of the PCM. Phase change materials with melting temperature less than 60°C are recommended for desalinating the saline water and to match the low operating temperatures of passive solar still (Rufuss *et al.*, 2016). Paraffin was found to be the best phase change materials for application in solar still. Due to the ready availability and chemically inert nature of paraffin, paraffin was opted in preference. In addition, uniform melting, medium storage, reliability, safety, moderate cost, and availability in the local market, was considered while selecting the PCM.

Thus, paraffin wax of having average melting temperature in the range of 58-59 °C has been chosen as the energy storage material since it is safe and easily available in the local market. Table 4.7 shows the physical property of paraffin wax and nano-PCM (Buonomo *et al.*, 2016; Rufuss *et al.*, 2016). Hence, CuO nanoparticle is used as a thermal conductivity enhancer with paraffin wax.

Table 4.7: Thermophysical properties of paraffin wax and CuO nanoparticles

Properties	Paraffin wax	Nano-PCM 3%
Melting temperature (°C)	58	56
Latent heat of fusion (kJ/kg °C)	180	168
Thermal conductivity (W/m K)	0.2	0.335
Specific heat capacity (J/kg K)	2100	2000
Density (kg/m ³)	840	894
T _{solidus} / T _{liquidus} (K)	321/335	321/335

Thermal energy storage is developed for solar still system to maintain approximately uniform desalination temperature and to continue the desalination process for a few additional hours when solar radiation is not available.

4.6.2.3.2 Size of NPCM

There are several ways to position the heat storage medium with respect to the basin. To extend the distillate time after sunset, the best way to position the NPCM reservoir is used beneath the v-corrugated absorber plate to reduce the heat losses and for construction simplicity. Heat is transferred from the absorber plate to the paraffin wax during the charging process and the reverse during discharging process for off-sunshine hours.

To determine the mass of NPCM, first let us determine the volume of v-corrugated absorber. In the present study, there is seven v-corrugated basins. The total volume of the NPCM can be estimated as follows:

$$V_{NPCM} = \frac{1}{2}(b \times h) \times l \times \text{no of v-corrugated} \dots\dots\dots (4.30a)$$

The mass of the NPCM can be calculated from,

$$m_{NPCM} = V_{NPCM} \times \rho_{NPCM} \dots\dots\dots (4.30b)$$

Where, m_{NPCM} and ρ_{NPCM} are mass and density of NPCM material, respectively. Substituting each value on the above equations yield. Substituting the values of $b = 0.14$ m, $h = 0.05$ m, $l = 1$ m and number of v-corrugated = 7 into equation (4.30a) yields the volume of the PCM estimated as, $V_{PCM} = 0.0245$ m³ and from equation (4.30b) the mass of PCM estimated is $m_{PCM} = 22$ kg.

4.6.2.3.3 Thermal Analysis of Latent Heat Storage System (LHS)

Thermal analysis of latent heat storage system comprises determination of melt fraction, charging, and discharging time. The process of storing heat energy in the latent heat storage material whereas it changes its phase from the solid state to the liquid state is called charging. The LHS is said to be fully charged when the entire PCM is completely melted, i.e., when the melt fraction reaches a value of one. The process of releasing heat energy in the latent heat storage material while it changes its phase from the liquid state to the solid-state is called discharging. The LHS is said to be fully discharged when the entire PCM is solidified, i.e., the melt fraction becomes zero.

- (a) Melt fraction: Melt fraction (θ_f) is referred to as the liquid fraction of the PCM when it exists in a liquid and solid phase form. The lowest temperature above which the material is in the liquid state is called liquidus temperature (T_L) and the highest temperature below which the material is completely in the solid state is called solidus temperature (T_S). Melt fraction (θ_f) of the PCM was obtained from the relationship (Gunjo *et al.*, 2018):

$$\theta_f = \left(\frac{T - T_S}{T_L - T_S} \right) = \frac{T - T_m + \Delta T_m}{2\Delta T_m} = \begin{cases} 0 & \text{for } T < T_S \\ 0-1 & \text{for } T_S \leq T \leq T_L \\ 1 & \text{for } T > T_L \end{cases} \dots\dots\dots (4.31)$$

Where T_m is the melting point of PCM.

- (b) Energy stored and discharged: energy gets stored in the PCM during the charging time and discharged from the PCM to the basin water during the discharging time in the form of sensible and latent heat.

Energy Stored: The total heat stored in the latent heat storage ($E_{T,Ch}$) consists of the sensible heat ($E_{S,Ch}$) and the latent heat ($E_{L,Ch}$). These can be obtained from the relationship (Niyas *et al.*, 2017).

$$E_{S,Ch} = m C_p (T - T_{int}) \dots\dots\dots (4.32)$$

$$E_{L,Ch} = m L_F \theta_f \dots\dots\dots (4.33)$$

$$E_{T,Ch} = m [C_p (T - T_{int}) + L_F \theta_f] \dots\dots\dots (4.34)$$

Energy recovered: The total heat discharged from the latent heat storage ($E_{T,Dis}$) consists of the sensible heat ($E_{S,Dis}$) and the latent heat ($E_{L,Dis}$). These are expressed as (Niyas *et al.*, 2017).

$$E_{S,Dis} = m C_p (T_{int} - T) \dots\dots\dots (4.35)$$

$$E_{L,Dis} = m L_F (1 - \theta_f) \dots\dots\dots (4.36)$$

$$E_{SH} = m [C_p (T_{int} - T) + L_F (1 - \theta_f)] \dots\dots\dots (4.37)$$

In general, the addition of nanoparticles to improve the stability of PCMs could be used to advantage in solar still applications. It was found that the charging and discharging rate is also enhanced when nanoparticles were embedded in the PCM.

4.6.2.4 Reflectors

The last modifications for the present study were adding internal reflectors to boost the solar intensity of the modified pyramid solar still. These reflectors are used to direct all solar rays that

come from sun and reflected from transparent glass to the v-corrugated absorber plate. Attaching internal reflectors to the vertical walls of solar still was used to increase solar reflectivity of solar radiation inside basin. To maximize the intensity solar rays, four internal reflective mirrors with dimensions of 1 m x 0.15 m were attached to the inner sidewalls of the saline water basin. Glass reflector was designated to reflect the radiation coming from glass cover to the water basin.

4.7 Conceptual Model and Design Specification of Solar Still Materials

The conceptual model of the system was developed using SOLIDWORKS 2021 software package. The pictorial view of conventional and modified pyramid solar still is shown in Figure 4.16.

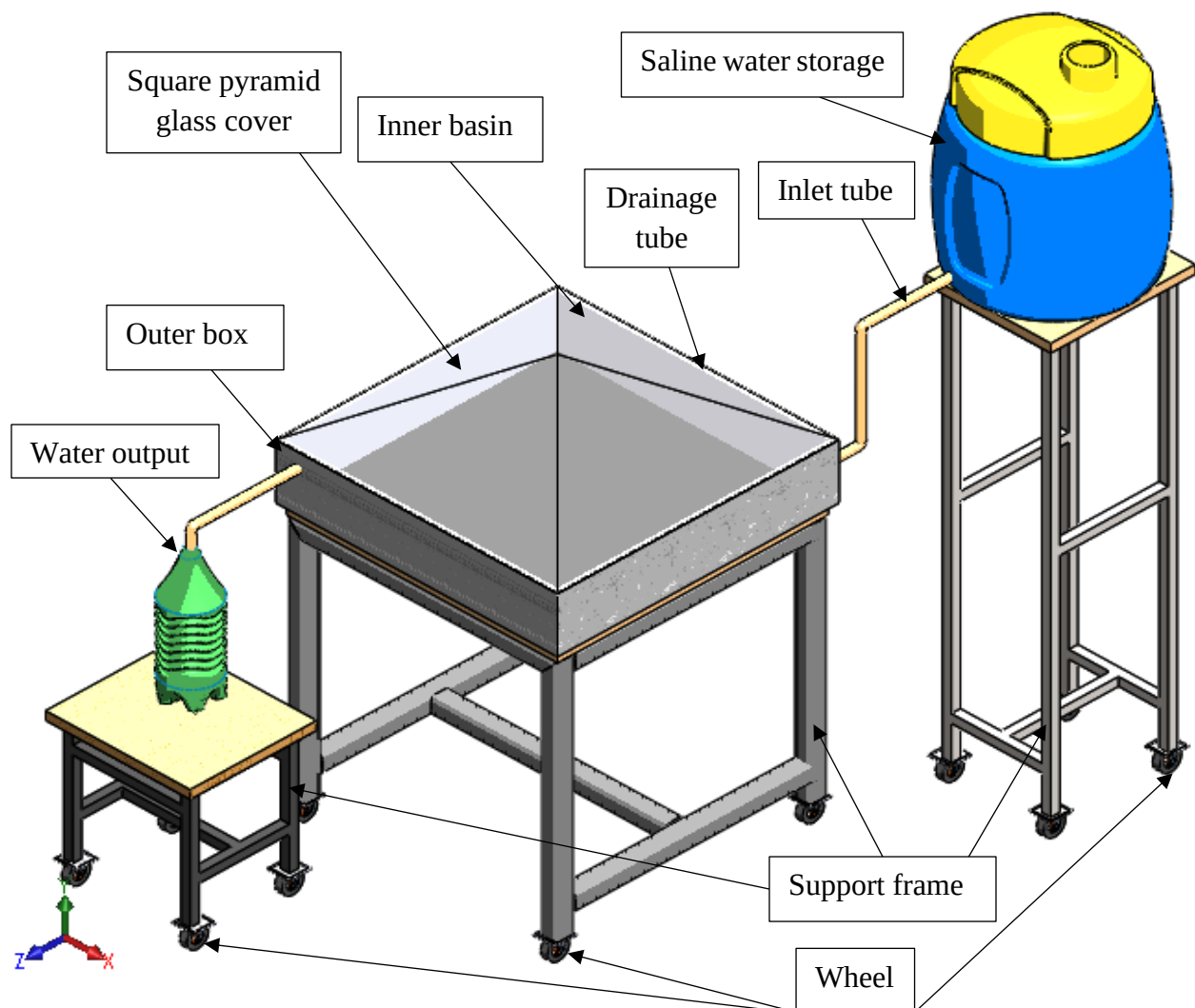


Figure 4.16: Pictorial view of pyramid solar still

For studying the experimental and theoretical aspects of solar stills conventional and modified solar stills specifications were described in Table 4.8.

Table 4.8: Design specifications and technical details of the solar stills

S. No	Items	Materials/Dimensions	
		CSS-BP	MSS-NDBP
1.	Absorber plate surface	Basin liner	V-corrugated shape basin
2.	Absorber coating	Black paint	Nano-CuO doped black paint
3.	Basin dimensions	1 m x 1 m	1 m x 1 m
4.	Glass cover or Top wall	Glass of 4 mm thickness	Glass of 4 mm thickness
5.	Bains and walls of still	Galvanized iron sheet	Galvanized iron sheet
6.	Insulation	Glass wool 0.05 m thick	Glass wool 0.05 m thick
7.	Bottom heat storage	-	Nano-embodied PCM
8.	Internal reflector	-	Glass reflector
9.	Outer box	Wood 0.02 m thick	Wood 0.02 m thick

4.8 Parameter Description of a Solar Still

Input design parameters which are used for analysis of energy and exergy were specified in this section. Table 4.9 shows the properties and main specifications of solar still materials which is used for theoretical analysis of conventional and modified solar stills (Jobrane *et al.*, 2022; Kabeel *et al.*, 2017; Belhadj *et al.*, 2015; Rajaseenivasan and Murugavel, 2013).

Table 4.9: The main specifications reference for solar still used in analyses

Material	Parameter	Symbols	Value and units
Glass cover	Mass of glass	m_g	7.737 kg/m^2
	Thickness	t_g	0.003 m
	Area of the glass surface	A_g	2.2 m^2
	Absorptivity of glass	α_g	0.05
	Transmissivity of glass	τ_g	0.88
	Emissivity of glass	ε_g	0.88
	Specific heat of glass	c_{pg}	800 J/kg K
	Mass of basin water	m_w	5.0 kg/m^2
	Area of basin water surface	A_w	1 m^2
	Absorptivity of water	α_w	0.05

Basin water or Water	Transmissivity of water	τ_w	0.9
	Emissivity of water	ε_w	0.96
	Specific heat of water	c_{pw}	4190 J/kg K
Absorber plate or Basin	Mass of absorber plate	m_p	7.80 kg/m ²
	Area of absorber plate	A_p	1 m ²
	Absorptivity of absorber plate	α_p	0.95
	Specific heat of absorber plate	$c_{p p}$	480 J/kg K
	Thickness of absorber plate	t_p	0.001 m
Insulating material	Thermal conductivity of insulation-1	k_{ins}	0.032 W/m K
	Thickness	t_{ins}	0.05 m
	Thermal conductivity of insulation-2 (Wood)	k_{ins}	0.04 W/m K
	Thickness	t_{ins}	0.02 m
Convection heat transfer coefficient		$h_{c, p-w}$	135 W/m ² K

4.9 Mechanisms of Heat and Mass Transfer Modes in a Solar Still

The solar distillation process basically involves three modes of heat transfer. The heat conduction takes place through the bottom and side walls, which results in a loss of heat from the still. This loss can be reduced by the usage of a thick insulation layer of insulating material. Heat from the basin is transferred to the saline water filled in the basin by the help of convection while thermal energy from the hot water is transferred onto the condensing glass cover by evaporation, convection and radiation. Then, water vapour condenses on the cover, yielding latent heat of condensation and distilled water is produced (Madhlopa, 2014). Figure 4.17 illustrates the various heat and mass transfer processes which occur in a solar still.

In turn, the glass cover dissipates heat to the environment by the help of convective and radiative heat transfer modes. It is vital to know that the internal heat transfer in solar still similarly includes mass transfer. Thus, special correlations are used to forecast the convective and evaporative heat transfer coefficients from the hot water to the surface of the transparent cover. Heat and mass transfer processes in a pyramid solar still can be categorized into (i) internal processes consisting of convection, radiation and evaporation and (ii) external processes which include conduction, convection and radiation.

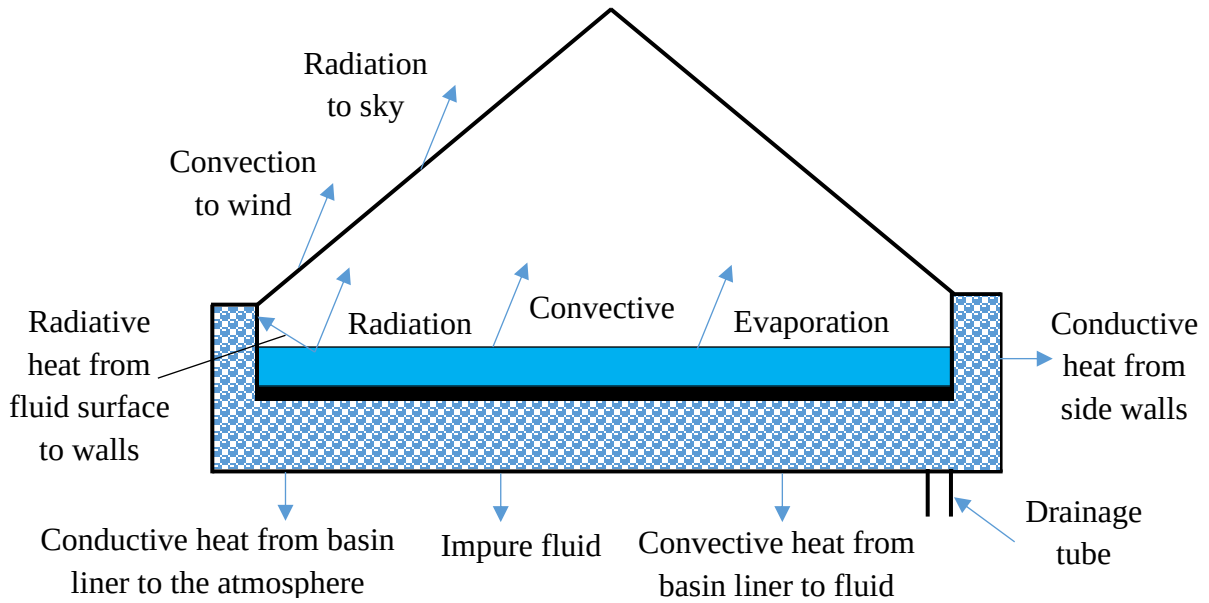


Figure 4.17: Heat transfer processes within a pyramid solar still

Various modes of heat transfer that occur inside and outside solar still was shown in Table 4.10.

Table 4.10: Various heat transfer modes inside and outside the solar still

Inside the solar still	Outside the solar still	Basin
- Convective heat transfer, $Q_{c, w-g}$ - Radiative heat transfer, $Q_{r, w-g}$ - Evaporative heat transfer, $Q_{e, w-g}$	- Convective heat transfer, $Q_{c, g-a}$ - Radiative heat transfer, $Q_{r, g-a}$ - Conductive heat from side wall and basin line, $Q_{c, s-a}$ and $Q_{c, b-a}$	Convective heat loss from water to basin, transfer, $Q_{c, w-b}$

4.9.1 Internal Heat Transmission

The various heat transfer modes that take place inside a solar still are convection, evaporation and radiation. The evaporation of saline water in the solar still depends on the energy received by the water basin in the solar still and the temperature of the inlet water. Internal modes of heat transfer occur from the basin water to glass cover through convection, evaporation and radiation as revealed in the above Figure 4.17.

The combined internal heat transfer occur from the basin water to glass cover by convection, evaporation and radiation is given by:

$$Q_{t, w-g} = Q_{c, w-g} + Q_{e, w-g} + Q_{r, w-g} \dots\dots\dots (4.38)$$

4.9.1.1 Convective Heat Transmission

Convective heat transmission generally refers to the convection where the heat is transmitted from one point to the other by the flow of the fluids. Such type of heat transmission can take place in fluids and gases. There are two types of convection that mean free or natural convection and forced convection. In the present solar still the convective heat transfer occurs among the saline water present in the basin to the inner surface of the glass cover. This phenomenon takes place due to the temperature variance between the components. The convection heat transfer from the water basin to the glass cover is given by equation (4.39a) (Altarawneh *et al.*, 2017):

$$Q_{c,w-g} = h_{c,w-g} A_b (T_w - T_g) \dots\dots\dots (4.39a)$$

The convective heat transfer coefficient ($h_{c,w-g}$) in between water and glass cover is obtained from an empirical relation, which is given by Dunkle. The relation is given by equation (4.39b):

$$h_{c,w-g} = 0.884 \left\{ (T_w - T_g) + \left[\frac{(P_w - P_g)(T_w + 273)}{(268.9 \times 10^3 - P_w)} \right] \right\}^{\frac{1}{3}} \dots\dots\dots (4.39b)$$

Where: $h_{c,w-g}$ - the convective heat transfer coefficient from water basin to glass cover

P_w - Saturated vapour pressures at water surface and determined by equation (4.39c)

P_g - Saturated vapour pressures at glass surface and determined by equation (4.39d)

T_w and T_g - Temperature of water surface and glass surface, respectively.

The following equations are used for predicting the saturated vapour pressures at water surface (4.39c) and glass surface (4.39d):

$$P_w = \exp \left(25.317 - \left(\frac{5144}{273 + T_w} \right) \right) \dots\dots\dots (4.39c)$$

$$P_g = \exp \left(25.317 - \left(\frac{5144}{273 + T_g} \right) \right) \dots\dots\dots (4.39d)$$

4.9.1.2 Evaporative Heat Transfer

Evaporative heat transfer refers to the evaporation that occurs within the still, which means that the liquid or water is converted to vapor form at a certain temperature. This occurs in solar still when solar radiation falls on the glass surface of the still and saline water evaporates. Therefore, evaporation occurs between water and vapor, which condenses on the inner surface of the glass. The internal evaporative heat transfer from the basin water surface to the glass cover plate is written as equation (4.40a) (Mahian *et al.*, 2017):

$$Q_{e,w-g} = h_{e,w-g} A_b (T_w - T_g) \dots\dots\dots (4.40a)$$

Some correlations for estimating the evaporative heat transfer coefficient from the water surface to the glass cover can be found in the literature. One of the most commonly used equations is Dunkle relation. The evaporative heat transfer coefficient ($h_{e, w-g}$) between water basin and glass cover is obtained from equation (4.40b):

$$h_{e, w-g} = (16.273 \times 10^{-3}) h_{c, w-g} \frac{(P_w - P_g)}{(T_w - T_g)} \dots\dots\dots (4.40b)$$

4.9.1.3 Radiation Heat Transfer

Radiative heat transfer occurs mainly due to the emission of body radiation. This type of heat transfer is free from any medium. In present solar still, radiative heat transfer is transmitted between the saline water in the basin to the inner surface of the cover glass. The radiative heat transfer from the saline water to the glass cover is determined by the equation (4.41a) (Katekar and Deshmukh, 2020).

$$Q_{r,w-g} = \sigma \varepsilon_{eff} A_b \left[(T_w + 273.15)^4 - (T_g + 273.15)^4 \right] \dots\dots\dots (4.41a)$$

In the new design, the heat is different on both sides of the radiant heat transfer from the water to the glass cover (Shanmugan *et al.*, 2020) and as following equation (4.41b):

$$Q_{r,w-g} = h_{r,w-g} A_b (T_w - T_g) \dots\dots\dots (4.41b)$$

The radiative heat transfer coefficient is found from by equating equation (4.41a) and (4.41b). Solving them and the radiative heat transfer coefficient ($h_{r, w-g}$) in between saline water and the inner side of the condenser glass cover is determined by the equation (4.41c):

$$h_{r, w-g} = \frac{\varepsilon_{eff} \sigma [(T_w + 273)^4 - (T_g + 273)^4]}{T_w - T_g} \dots\dots\dots (4.41c)$$

Simplifying equation (4.41c) and the heat transfer coefficient due to radiation is given by (4.41d):

$$h_{r, w-g} = \varepsilon_{eff} \sigma \left[(T_w + 273)^2 + (T_g + 273)^2 \right] \times \left[(T_w + T_g + 546) \right] \dots\dots\dots (4.41d)$$

Where, σ is Stefan Boltzmann constant and its value was $5.669 \times 10^{-8} \text{ W m}^2 \text{ K}^4$. The equivalent emissivity factor (ε_{eff}) between water and glass was given by equation (4.41e):

$$\varepsilon_{eff} = \left[\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1 \right]^{-1} \dots\dots\dots (4.41e)$$

Where: ϵ_w and ϵ_g - emissivity of water and glass, respectively. Its value $\epsilon_w = 0.96$ and $\epsilon_g = 0.88$. The total coefficient of internal heat transfer from the basin water surface to the glass cover caused by convection, evaporation, and radiation is determined by the equation (4.42):

$$h_{t,w-g} = h_{r,w-g} + h_{c,w-g} + h_{e,w-g} \dots\dots\dots(4.42)$$

4.9.2 External Heat Transmission

The external heat transfer in a solar still takes place with the help of conduction, convection and radiation. In the present still the external heat transmission is considered to take place from the solar still to the atmosphere. Such type of heat loss is top loss heat transfer. Bottom and side loss heat transfer are also a type of external heat transfer process. The new design has been contributed to external heat transfer modes such as radiative and convective heat transfer modes, was shown in Figure 4.17. External heat transfer is only heat loss through the top, bottom and side walls.

4.9.2.1 Top Loss Heat Transfer

Heat transfer from the surroundings is mostly in the form of convection and radiation. It is mainly due to the heat taken away by the wind from the glass surface, side walls and bottom of the solar still. The heat loss from the side walls and the bottom can be reduced by insulation layers. Glass cover with a thickness of 4 mm that acts as a uniform heat schedule for the convective and radiative process. The convective and radiative heat loss from the condensed glass cover to the atmosphere is required to find the minimum thickness of glass; they can be estimated as follows:

The external heat transfer loss from the glass cover to ambient can be estimated by equation (4.43):

$$Q_{t,g-a} = Q_{c,g-a} + Q_{r,g-sky} \dots\dots\dots(4.43)$$

4.9.2.1.1 Convective Heat Transfer between Glass and Ambient

The heat in the form of convection over the glass surface reduces the glass temperature, which increases the driving force of higher water to the glass temperature difference. The convective heat transfer from the glass cover to the ambient given by equation (4.44a) (Jobrane *et al.*, 2022):

$$Q_{c,g-a} = h_{c,g-a} A_g (T_g - T_{at}) \dots\dots\dots(4.44a)$$

The convective heat transfer from the still is a function of wind flowing around the still. The convective heat transfer coefficient losses from the glass cover and atmosphere are given by following relations (4.44b) and (4.44c):

$$h_{c,g-a} = 2.8 + 3.0 V \quad \text{If } V < 5 \text{ m/s} \dots\dots\dots(4.44b)$$

$$h_{c,g-a} = 5.7 + 3.8 V \quad \text{If } V > 5 \text{ m/s} \dots\dots\dots (4.44c)$$

4.9.2.1.2 Radiative Heat Transfer between Glass and Ambient

The radiative heat transfer outside the solar still is a function of sky (T_{sky}) and glass temperature. Radiative heat transfer from glass cover to sky is given by equation (4.45a):

$$Q_{r,g-sky} = h_{r,g-sky} A_g (T_g - T_{sky}) \dots\dots\dots (4.45a)$$

The radiation heat transfer from the glass to the sky is estimated by equation (4.45b) as follows

$$Q_{r,g-sky} = \varepsilon_g \sigma A_g \left[(T_g + 273)^4 - (T_{sky} + 273)^4 \right] \dots\dots\dots (4.45b)$$

Besides, radiative heat transfer coefficient losses between the glass and sky are given by (4.45d):

$$h_{r,g-sky} = \frac{\varepsilon_g \sigma \left[(T_g + 273)^4 - (T_{sky} + 273)^4 \right]}{(T_g - T_{sky})} \dots\dots\dots (4.45c)$$

$$h_{r,g-sky} = \varepsilon_g \sigma \left[(T_g + 273)^2 + (T_{sky} + 273)^2 \right] \times (T_g + T_{sky} + 546) \dots\dots\dots (4.45d)$$

The sky temperature is given as a function of ambient temperature, which is calculated using the equation (4.45e) as reported by (Kabeel *et al.*, 2017):

$$T_{sky} = T_a - 6 \dots\dots\dots (4.45e)$$

The total coefficient of heat loss from the glass to the atmosphere is found by the equation (4.46):

$$h_{t,g-a} = h_{c,g-a} + h_{r,g-sky} \dots\dots\dots (4.46)$$

4.9.2.2 Bottom and Side Loss Heat Transfer

The heat is lost from the basin to the atmosphere through the sidewalls and bottom of the basin by conduction, convection and radiation. The heat loss from the basin to the surrounding is calculated using the equation (4.47) (Shanmugan *et al.*, 2020):

$$Q_{b,p-a} = U_b A_b (T_p - T_a) \dots\dots\dots (4.47)$$

For the still with a deep basin, the reduction in water mass due to evaporation is negligible. But in the shallow basin still, the effect of evaporated water mass on the still performance is important. Here, the evaporated water is continuously replaced and water mass in the basin is assumed to be constant. Assumed that, the makeup water is at atmospheric temperature and takes heat from basin. If the side area of still (A_s) is very small, compared with the basin liner area of still (A_b) then side heat loss coefficient can be neglected (Agrawal *et al.*, 2017).

4.10 Energy Analysis

Energy analysis aims to develop equations for study of the temperature of various components of solar still such as glass cover, saline water, absorber plate and NPCM layer. Some of the solar irradiation falling on the glass cover passes through it, and the rest is reflected in the atmosphere. Part of the solar energy that enters is absorbed by the glass itself and the remaining amount reaches the saline water surface in the basin. A small part of the energy is reflected from the surface of the saline water and the rest passes through it to the absorber plate. A schematic representation of energy balance for solar still is shown in Figure 4.18.

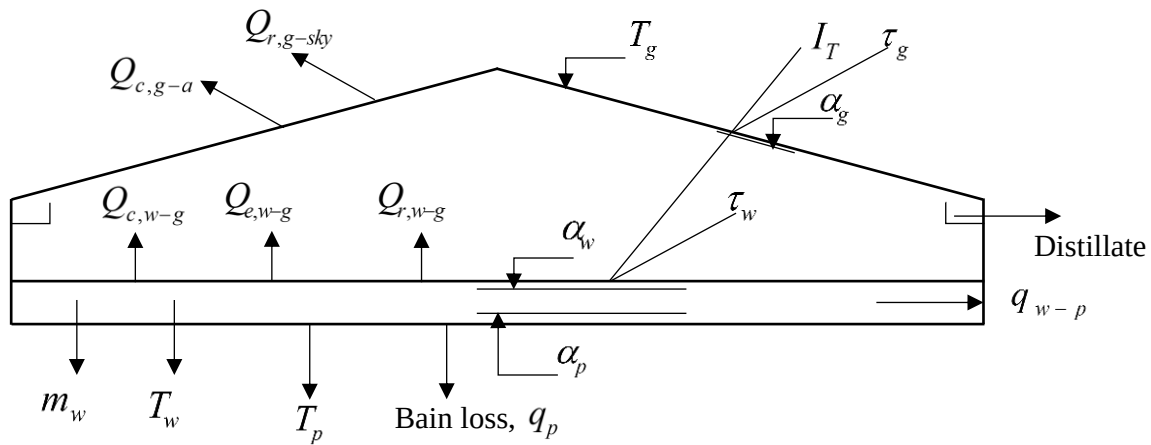


Figure 4.18: Schematic illustration of energy balance for solar still

Assumption of Solar Stills

The thermal modeling of solar stills was developed using energy balance equations. The following assumptions are used in the development of the energy balance equation:

- All the thermodynamic processes are under steady state.
- No heat loss because of the air tight basin.
- The solar still adiabatically insulated without leakage of vapors.
- The heat capacity of insulating materials (side and bottom), influence of pressure drop, kinetic, potential, and chemical effects are negligible.
- Uniform saline water and condenser glass cover temperature.
- All properties of saline water are supposed to be similar to that of water for simplicity.
- Attenuation of solar energy within the saline water is not considered.
- Thermal properties of materials used in solar still are given in Table 4.9.

Thermal resistance network is an electrical analogy to calculate the heat transfer through the system. Figure 4.19 illustrates the thermal resistance network for solar still with and without PCM.

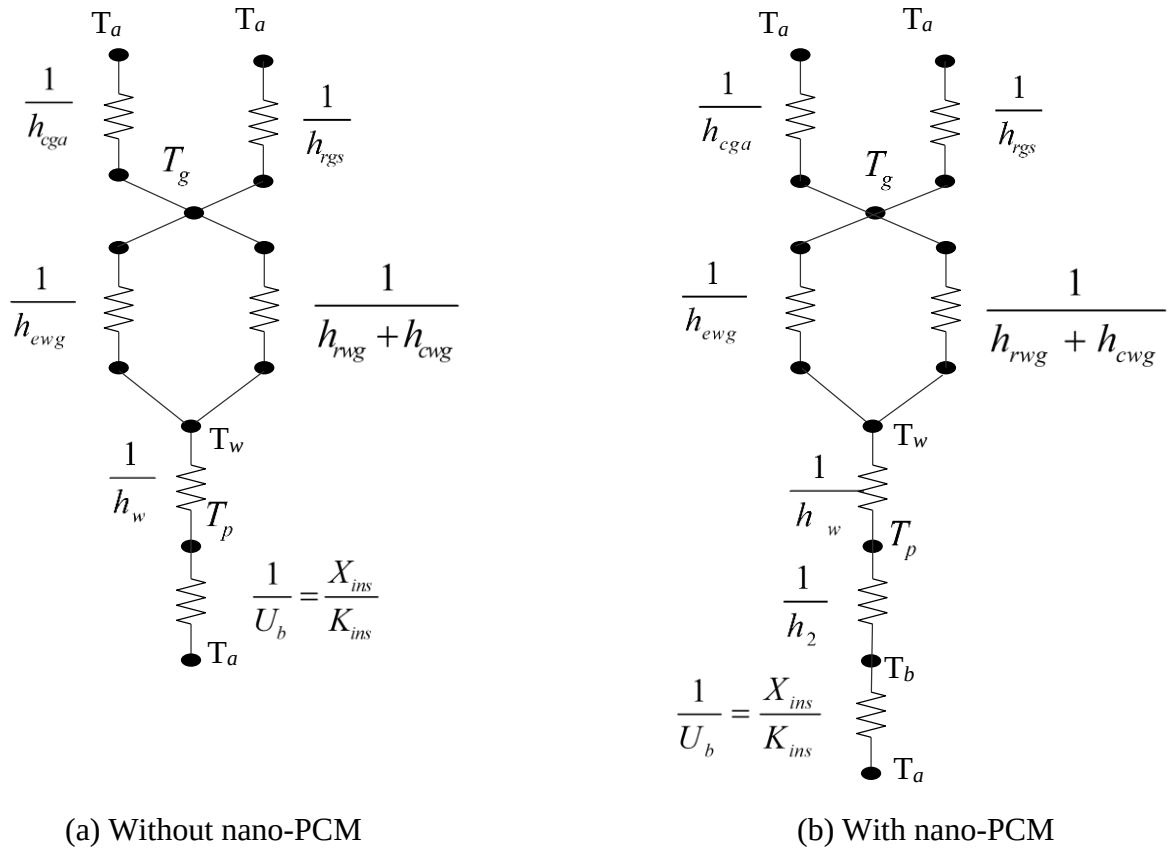


Figure 4.19: Thermal resistance network for solar still

More quantity of energy is absorbed by absorber plate and some of the energy is reflected by it. Energy from the absorber plate is transported to the saline water and NPCM layer beneath the absorber. The NPCM stores the energy that is lost from the absorber plate of the solar still. However, a negligible portion of the energy is lost due to conduction through the lower insulation. The equations used to calculate the theoretical calculations were referred from Dunkle model as reported by (Katekar and Deshmukh, 2020; Sharshir *et al.*, 2017). The energy balance equation for glazing cover, saline water used in the basin, basin absorber plate and nano-PCM of the still can be estimated as follows:

4.10.1 Energy Balance of Solar Still Components

The energy balance equations are written for thermal modeling of conventional and modified pyramid solar still. Referring to the schematic diagram of heat transfer analogy presented in section

4.9, Figure 4.17 and based on the above assumptions, the energy balance equations for the conventional and improved solar still are given as following.

4.10.1.1 Energy Balance of Glass Cover

The heat taken by the bottom surface of glass cover from basin water conducts through the glass thickness. The top surface of the glass cover in turn transfers this heat to the atmosphere by convection and radiation due to the temperature difference between glass, atmosphere and sky. It is assumed that the temperature of the glass material is constant throughout the material. It is also assumed that, the heat flow from the basin is uniform over the surface and both the covers receive same amount of heat. Energy balance for glass cover is expressed as follows:

$$\begin{array}{ccccccc} \text{Energy absorbed} & & \text{Energy absorbed by} & & \text{Energy stored} & & \text{Energy loss from the} \\ \text{by the top surface} & + & \text{bottom surface of} & = & \text{in the glass} & + & \text{top surface of the} \\ \text{of the glass cover} & & \text{the glass cover} & & & & \text{glass} \end{array}$$

The energy balance in glass cover is shown in Figure 4.20.

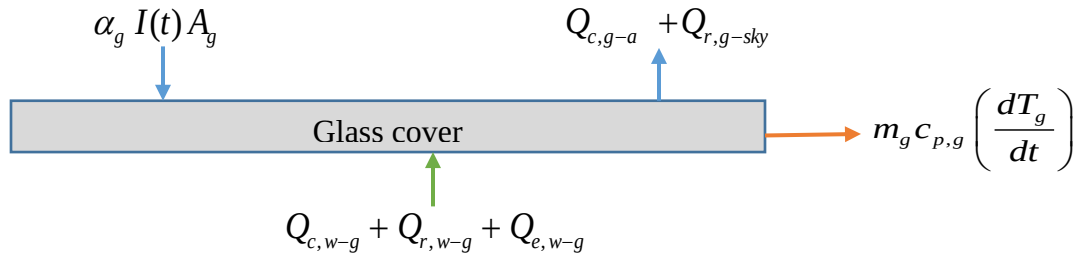


Figure 4.20: Heat Energy balance of a glass cover

The energy received by the glass cover from solar radiation as well as from saline water in the basin by convection, evaporation and radiation. The energy is lost from the glass cover to the atmosphere by convection and radiation. From the above Figure 4.20, the energy balance in glazing cover is given by equation (4.48a):

$$\alpha_g I(t) A_g + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} = m_g c_{p,g} \left(\frac{dT_g}{dt} \right) + Q_{c,g-a} + Q_{r,g-sky} \dots\dots\dots (4.48a)$$

$$\alpha_g I(t) A_g + h_{t,w-g} A_w (T_w - T_g) = m_g c_{p,g} \left(\frac{dT_g}{dt} \right) + h_{c,g-a} A_g (T_g - T_a) + h_{r,g-sky} A_g (T_g - T_{sky}) \dots\dots\dots (4.48b)$$

Where: $h_{t,w-g}$ is the summation of convection, radiation, and evaporation heat transfer coefficients between saline water and the inner surface of the glass cover and estimated from equation (4.42).

$$m_g c_{p,g} \left(\frac{dT_g}{dt} \right) = \alpha_g I(t) A_g + h_{t,w-g} A_w (T_w - T_g) - h_{c,g-a} A_g (T_g - T_a) - h_{r,g-sky} A_g (T_g - T_{sky}) \dots (4.48c)$$

The transient energy balance equation for the glass cover is determined by using equation (4.48d)

$$T_g^{i+1} = T_g^i + \frac{\Delta t}{m_g c_{p,g}} \left\{ \alpha_g I(t) A_g + h_{t,w-g} A_w (T_w^i - T_g^i) - h_{c,g-a} A_g (T_g^i - T_a^i) - h_{r,g-sky} A_g (T_g^i - T_{sky}^i) \right\} \dots (4.48d)$$

Where: I(t) is the solar radiation influx on the glass cover and can be found using equation (4.16c).

4.10.1.2 Energy Balance of Saline Water in Basin

Saline water receives solar energy transmitted from the condenser glass cover as well as from absorber plate. Energy received by the saline water in the still (from sun and absorber plate) is equal to the summation of energy lost by convective, evaporative and radiative heat transfer between the saline water and glass, and also energy gained by the saline water. Energy balance for saline water is estimated as follows.

Energy absorbed by basin water surface	+	Energy absorbed by water due to evaporation	=	Energy stored in water	+	Heat loss from water to glass due to convection, radiation, and evaporation
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The energy balance for saline water used in the basin is shown in Figure 4.21.

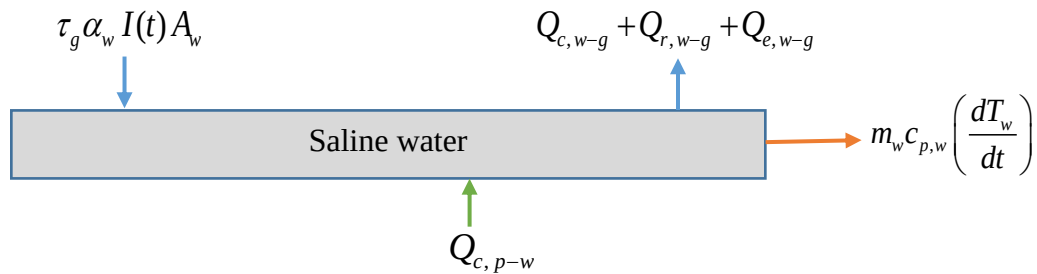


Figure 4.21: Energy balance diagram of brackish water in basin

The energy balance equation for the saline water is as follows:

$$\tau_g \alpha_w I(t) A_w + Q_{c,p-w} = m_w c_{p,w} \left(\frac{dT_w}{dt} \right) + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} \dots (4.49a)$$

The convective heat transfer between basin and water was taken (Zurigat and Abu, 2004) as

$$Q_{c,p-w} = h_{w,p-w} A_p (T_p - T_w) \dots (4.49b)$$

$$\tau_g \alpha_w I(t) A_w + h_w A_p (T_p - T_w) = m_w c_{p,w} \left(\frac{dT_w}{dt} \right) + h_t A_w (T_w - T_g) \dots (4.49c)$$

The energy balance equation for the saline water is given by equation (4.49d).

$$m_w c_{p,w} \left(\frac{dT_w}{dt} \right) = \tau_g \alpha_w I(t) A_w + h_w A_p (T_p - T_w) - h_t A_w (T_w - T_g) \dots (4.49d)$$

The transient energy balance equation for the saline water is calculated by using equation (4.49e)

$$T_w^{i+1} = T_w^i + \frac{\Delta t}{m_w c_{p,w}} \left\{ \tau_g \alpha_w I(t) A_w + h_w A_p (T_p^i - T_w^i) - h_t A_w (T_w^i - T_g^i) \right\} \dots (4.49e)$$

The heat transfer coefficient due to convection between absorber plate and saline water was taken as 135 W/m² K (Zurigat and Abu, 2004).

4.10.1.3 Energy Balance of Absorber Plate with PCM

Absorber plate receives energy from solar irradiation. Out of that, some amount is stored in absorber plate, transported to PCM and the remaining amount is utilized to evaporate the water. Energy received by the basin plate, is equal to the summation of the energy gained by the basin plate, energy lost by convection heat transfer between the basin and water, and also side losses.

The energy balance for absorber plate used in the basin is shown in Figure 4.22.

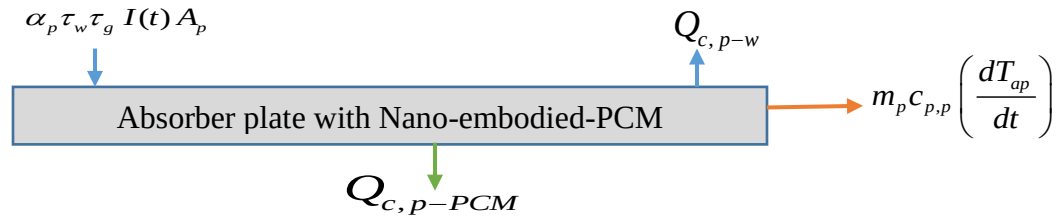


Figure 4.22: Energy balance diagram of absorber plate

The energy balance for the absorber plate is given by.

Energy absorbed by basin absorber plate	=	Energy stored in absorber plate	+	Heat transferred to water due to evaporation	+	Heat lost from the basin to surroundings due to various heat transfer modes
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From the above Figure 4.22, the energy balance for absorber plate is given by:

$$\alpha_p \tau_g \tau_w I(t) A_p = m_p c_p \left(\frac{dT_p}{dt} \right) + Q_{c,p-w} + Q_{PCM} \dots (4.50a)$$

The heat quantity Q_{PCM} stored in PCM from the absorber plate to paraffin depends on the thermal conductivity k of the PCM and insulation material used around the basin and its thickness x .

$$\alpha_p \tau_g \tau_w I(t) A_p = m_p c_p \left(\frac{dT_p}{dt} \right) + h_w A_p (T_p - T_w) + \left(\frac{K_{PCM}}{X_{PCM}} \right) A_p (T_p - T_{PCM}) \dots (4.50b)$$

The energy balance equation for absorber plate is expressed by equation (4.50c):

$$m_p C_p \left(\frac{dT_p}{dt} \right) = \alpha_p \tau_g \tau_w I(t) A_p - h_w A_p (T_p - T_w) - \left(\frac{K_{PCM}}{X_{PCM}} \right) A_p (T_p - T_{PCM}) \dots\dots\dots (4.50c)$$

The transient energy balance equation for the absorber plate with PCM is given by equation (4.50d)

$$T_p^{i+1} = T_p^i + \frac{\Delta t}{m_p C_p} \left\{ \alpha_p \tau_g \tau_w I(t) A_p - h_w A_p (T_p^i - T_w) - \left(\frac{K_{PCM}}{X_{PCM}} \right) A_p (T_p^i - T_{PCM}^i) \right\} \dots\dots\dots (4.50d)$$

4.10.1.4 Energy Balance Equation for PCM

The phase change material stores the transferred energy from the absorber plate and dissipates the small amount of energy to the environment through the bottom surface of solar still. The energy balance for nano-PCM used in the basin is shown in Figure 4.23.

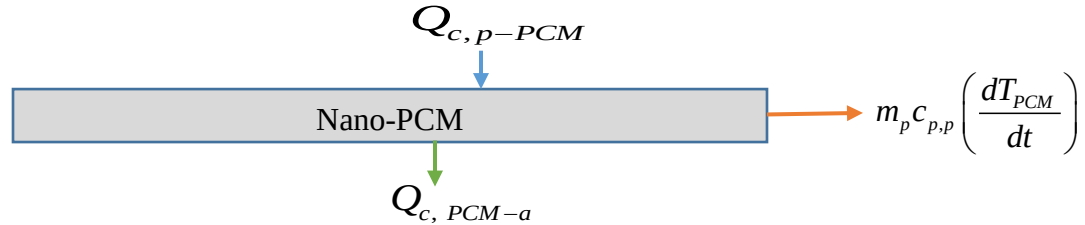


Figure 4.23: Energy balance diagram of PCM

Energy balance for Nano-PCM is expressed as follows (Sarhaddi *et al.*, 2017):

$$\left(\frac{K_{PCM}}{X_{PCM}} \right) (T_p - T_{PCM}) = \left(\frac{K_{ins}}{X_{ins}} \right) (T_{PCM} - T_a) + \frac{M_{equ,PCM}}{A_p} \left(\frac{dT_{PCM}}{dt} \right) \dots\dots\dots (4.51a)$$

$$\frac{M_{equ,PCM}}{A_p} \left(\frac{dT_{PCM}}{dt} \right) = \left(\frac{K_{PCM}}{X_{PCM}} \right) (T_p - T_{PCM}) - \left(\frac{K_{ins}}{X_{ins}} \right) (T_{PCM} - T_a) \dots\dots\dots (4.51b)$$

The transient energy balance equation for the PCM is determined by using equation (4.51c)

$$T_{PCM}^{i+1} = T_{PCM}^i + \frac{\Delta t \times A_p}{M_{equ,PCM}} \left\{ \left(\frac{K_{PCM}}{X_{PCM}} \right) (T_p^i - T_{PCM}^i) - \left(\frac{K_{ins}}{X_{ins}} \right) (T_{PCM}^i - T_a^i) \right\} \dots\dots\dots (4.51c)$$

The equivalent heat capacity of PCM (M_{equ}) during the state change from solid to liquid is given by (4.51d), (4.51e) and (4.51f) (Rufuss *et al.*, 2016):

$$M_{equ} = m_{PCM} \times C_{s,PCM} \quad \text{for } T_{PCM} < T_m \dots\dots\dots (4.51d)$$

$$M_{equ} = m_{PCM} \times L_{PCM} \quad \text{for } T_m \leq T_{PCM} < T_m + \delta \dots\dots\dots (4.51e)$$

$$M_{equ} = m_{PCM} \times C_{L,PCM} \quad \text{for } T_{PCM} > T_m + \delta \dots\dots\dots (4.51f)$$

4.10.1.5 Energy Balance Equation for Absorber Plate without PCM

Absorber plate receives energy from solar irradiation. Out of that, some amount of heat is lost to the atmosphere and absorber plate and the remaining amount is utilized to evaporate the water. Energy received by the basin plate, is equal to the summation of the energy gained by the basin plate, energy lost by convection heat transfer between the basin and water and side losses. The energy balance for the absorber plate is given by:

Energy absorbed by basin absorber plate = Energy stored in absorber plate + Heat transferred to water due to evaporation + Heat lost from the basin to surroundings due to various heat transfer modes

The energy balance for absorber plate without PCM used in the basin is shown in Figure 4.24.

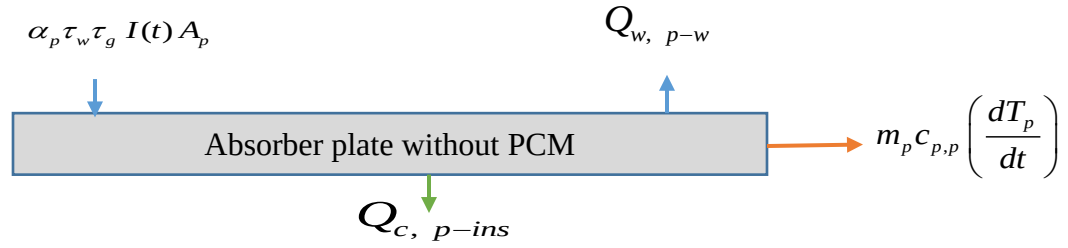


Figure 4.24: Energy balance diagram of absorber plate without PCM

From the above Figure 4.24, the energy balance for absorber plate without PCM is given by:

$$\alpha_p \tau_g \tau_w I(t) A_p = m_p c_p \left(\frac{dT_p}{dt} \right) + Q_{w, p-w} + Q_{loss} \dots \dots \dots (4.52a)$$

The heat quantity Q_{loss} to ambient from the absorber plate depends on the thermal conductivity k of the insulation material used around the basin and its thickness x . The heat loss from basin to ambient was taken as (Sebaili and Khallaf, 2020)

$$Q_{lost} = U_p A_p (T_p - T_{ins.}) \text{ and } U_{ap} = \frac{k_{ins.}}{x_{ins.}} \dots \dots \dots (4.52b)$$

$$\alpha_p \tau_g \tau_w I(t) A_p = m_p c_p \left(\frac{dT_p}{dt} \right) + h_w A_p (T_p - T_w) + U_p A_p (T_p - T_{ins.}) \dots \dots \dots (4.52c)$$

The energy balance equation for absorber plate without PCM is expressed by equation (4.52d):

$$m_p C_p \left(\frac{dT_p}{dt} \right) = \alpha_p \tau_g \tau_w I(t) A_p - h_w A_p (T_p - T_w) - \left(\frac{K_{ins.}}{X_{ins.}} \right) A_p (T_p - T_{ins.}) \dots \dots \dots (4.52d)$$

The transient energy balance equation for the basin plate without PCM is given by equation (4.52e)

$$T_p^{i+1} = T_p^i + \frac{\Delta t}{m_p C_{p,p}} \left\{ \alpha_p \tau_g \tau_w I(t) A_p - h_w A_p (T_p^i - T_w^i) - \left(\frac{K_{ins.}}{X_{ins.}} \right) A_p (T_p^i - T_{ins.}^i) \right\} \dots\dots\dots (4.52e)$$

4.10.1.6 Energy efficiency

The hourly yield (m_{ew} , $\text{kg m}^{-2} \text{h}^{-1}$) is calculated as the ratio of the evaporative heat flux and the latent heat of water vaporization (h_{fg} , J. kg^{-1}). The freshwater productivity per area of the basin (m_{ew} , kg/m^2) is calculated by using equation (4.53a) (Jobrane *et al.*, 2022):

$$m_{ew} = \frac{Q_e \times 3600}{h_{fg}} \dots\dots\dots (4.53a)$$

$$m_{ew} = \frac{h_{ew} \times A_p \times (T_w - T_g) \times 3600}{h_{fg}} \dots\dots\dots (4.53b)$$

The performance of the solar still could be analyzed by evaluating the thermal efficiency of the process. The thermal or energy efficiency of a solar still can be computed as the ratio of evaporative heat transfer (total productivity) to the incident solar irradiation on the absorber plate. Therefore, the thermal efficiency is given by equation (4.53c) (Shoeibi *et al.*, 2021):

$$\eta_{th} = \frac{\sum m_{ew} h_{fg}}{3600 \times A_p \times \sum I(t)} \dots\dots\dots (4.53c)$$

Where the latent heat of vaporization (h_{fg}) of water can be estimated as (Sahota and Tiwari, 2017):

$$h_{fg} = 3.1615(10^6 - 761.6 T_i) \quad \text{for } T_i > 70 \dots\dots\dots (4.53d)$$

$$h_{fg} = 2.4935(10^6 - 947.79 T_i + 0.13132 T_i^2 - 0.0047974 T_i^3) \quad \text{for } T_i < 70 \dots\dots\dots (4.53e)$$

where $I(t)$, m_{ew} , A_p and h_{fg} are the total daily radiation, the daily freshwater yield, area of the absorber plate and the latent heat of water, respectively.

4.11 Exergy Analysis

Exergy is a tremendous gadget used to classify and understand the reasons of the system inadequacies as well as determine the magnitude and location of these inefficiencies. For solar desalination systems, limited research works were found in the literature on exergy analysis compared with energy analysis. There is a need to analyze the solar desalination process based on exergy concept. To find out the place where more losses is taking place, the exergy destruction in the various components of the solar still was evaluated.

The exergy performance based on second law of thermodynamics was evaluated to quantify the losses in solar still under different climatic conditions. Exergy analysis uses the basis mass and energy conservation with the second law of thermodynamics to help us in finding the following:

- (1) It can be utilized to define the kind, and magnitude of energy losses in a system and locate it,
- (2) It can be utilized to find ways to decrease losses and ways to increase the efficiency of energy systems (Mohamed *et al.*, 2019).

4.11.1 Fundamental Concept of Exergy and Exergy Efficiency of Solar Still

One of the main objectives of the exergy analysis is to locate and characterize the causes of exergy destruction or exergy losses, as well as to quantify the corresponding rates. Based on the second law of thermodynamics, exergy of the system was calculated. It evaluated the maximum amount of work extracted from the given quantity of energy input. The formulas used to find out the exergy efficiency of solar still are reported by (Sethi and Dwivedi, 2013).

The general exergy balance equation can be written as equation (4.54a):

$$Ex_{dest} = Ex_{in} - Ex_{out} \dots\dots\dots (4.54a)$$

For a solar still, equation (4.54a) can be rewritten as equation (4.54b):

$$Ex_{dest} = Ex_{sun} - (Ex_{evap} + Ex_{work}) \dots\dots\dots (4.54b)$$

In a solar still, exergy input is based on the radiation entering the basin. This can be written as (Aghaei *et al.*, 2013):

$$Ex_{sun} = A_g \times I(t)_s \times \left[1 - \frac{4}{3} \times \left(\frac{T_a + 273}{T_s} \right) + \frac{1}{3} \times \left(\frac{T_a + 273}{T_s} \right)^4 \right] \dots\dots\dots (4.54c)$$

Where: T_a is the ambient temperature and T_s is the temperature of the sun ($T_s = 6000$ K).

The exergy of work rate of a solar still is given by

$$Ex_{work} = 0 \dots\dots\dots (4.54d)$$

Exergy evaporation or output is the result of the evaporation and condensation of the saline water. The hourly exergy output was calculated from equation (4.54e) (Abdelgaied *et al.*, 2022):

$$Ex_{evap} = \frac{m_{evap} \times h_{fg}}{3600} \times \left[1 - \left(\frac{T_a + 273}{T_w + 273} \right) \right] \dots\dots\dots (4.54e)$$

4.11.2 Exergy Destruction of Solar Still Components

The exergy balance equations of the three main components of the solar still such as absorber plate, saline water and glass cover are given below (Ranjan *et al.*, 2016).

4.11.2.1 Exergy Balance of a Glass Cover

The exergy input for the glass cover is the sum of the fraction of solar exergy ($\alpha_g Ex_{sun}$) absorbed by glass cover and the exergy associated with the heat transfer between saline water surface and the inner side of the glass cover ($Ex_{t, w-g}$). A part of this exergy is lost to the atmosphere by convection and radiation heat transfer and remaining is destroyed (Ex_{des-g}).

The exergy balance in glass cover is shown in Figure 4.25.

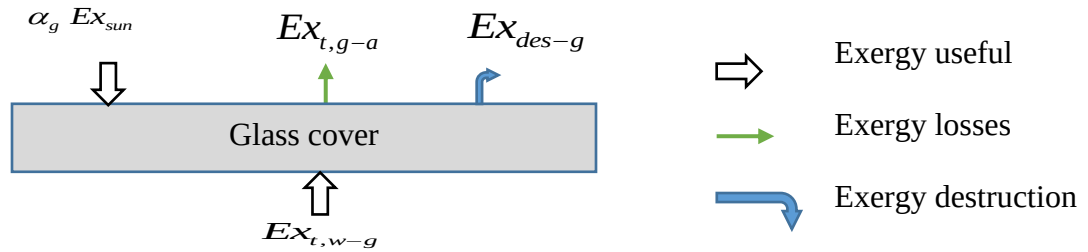


Figure 4.25: Exergy balance of a glass cover

Exergy balance for the glass cover is expressed as equation (4.55a)

Exergy input absorbed by the top of the glass cover	+	Exergy absorbed by bottom surface of the glass cover	=	Exergy losses to the atmosphere	+	Exergy destruction of the glass
---	---	--	---	---------------------------------------	---	------------------------------------

$$Ex_{des,g} = \alpha_g Ex_{sun} + Ex_{t,w-g} - Ex_{t,g-a} \dots\dots\dots (4.55a)$$

The sun exergy rate (Ex_{sun}) is calculated by using equation (4.54c). $Ex_{t, w-g}$: is the exergy related with the heat transfer through evaporation, convection and radiation between water and inner side of the glass cover and calculated using equation (4.55b).

$$Ex_{t,w-g} = Ex_{e,w-g} + Ex_{c,w-g} + Ex_{r,w-g} \dots\dots\dots (4.55b)$$

The evaporative exergy rate of glass cover is calculated by using equation (4.55c)

$$Ex_{e,w-g} = h_{e,w-g} A_w (T_w - T_g) \times \left[1 - \frac{T_a + 273}{T_w + 273} \right] \dots\dots\dots (4.55c)$$

where $h_{e,w-g}$ is the evaporative heat transfer coefficient between water and glass cover ($W/m^2 K$) and determined from equation (4.40b).

The convective exergy rate of glass cover is calculated by using equation (4.55d)

$$Ex_{c,w-g} = h_{c,w-g} A_w (T_w - T_g) \left(1 - \frac{T_a + 273}{T_w + 273} \right) \dots\dots\dots (4.55d)$$

where $h_{c,w-g}$ is the convective heat transfer coefficient between water and glass cover ($W/m^2 K$) and determined from equation (4.39b).

The radiative exergy rate of glass cover is calculated by using equation (4.55e)

$$Ex_{r,w-g} = h_{r,w-g} A_w (T_w - T_g) \times \left[1 - \frac{4}{3} \times \left(\frac{T_a + 273}{T_w + 273} \right) + \frac{1}{3} \times \left(\frac{T_a + 273}{T_w + 273} \right)^4 \right] \dots\dots\dots (4.55e)$$

where $h_{r,w-g}$ is the radiative heat transfer coefficient between water and glass cover ($W/m^2 K$) and determined from equation (4.41d).

$Ex_{t,g-a}$: is the exergy associated with the heat transfer through convection and radiation between outer glass cover and atmosphere and is calculated using equation (4.55f).

$$Ex_{t,g-a} = Ex_{c,g-a} + Ex_{r,g-a} \dots\dots\dots (4.55f)$$

Convective exergy loss rate from the glass cover to ambient is obtained from equation (4.55g):

$$Ex_{c,g-a} = h_{c,g-a} A_g (T_g - T_a) \times \left[1 - \frac{T_a + 273}{T_g + 273} \right] \dots\dots\dots (4.55g)$$

where $h_{c,g-a}$ is the convective heat transfer coefficient between glass cover and atmosphere ($W/m^2 K$) and estimated from equation (4.44c).

Radiative exergy loss rate from the glass cover to ambient is obtained from equation (4.55h)

$$Ex_{r,g-a} = h_{r,g-a} A_g (T_g - T_a) \times \left[1 - \frac{4}{3} \times \left(\frac{T_a + 273}{T_g + 273} \right) + \frac{1}{3} \times \left(\frac{T_a + 273}{T_g + 273} \right)^4 \right] \dots\dots\dots (4.55h)$$

where $h_{r,g-a}$ is the radiative heat transfer coefficient between glass cover and atmosphere ($W/m^2 K$) and estimated from equation (4.45d).

4.11.2.2 Exergy Balance of a Saline Water

Exergy input for the saline water is the sum of the fraction of solar exergy ($\tau_g \alpha_w Ex_{sun}$) absorbed by water and the useful exergy from the basin which is used to raise the temperature of saline water (Ex_w). A part of it is used as the exergy related with the heat transfer between saline water surface and the inner side of the glass cover ($Ex_{t,w-g}$) and remaining is destroyed (Ex_{des-w}).

$$\begin{array}{ccccccc} \text{Exergy input for} & + & \text{Useful exergy from basin} & = & \text{Exergy} & + & \text{Exergy useful from} \\ \text{the saline water} & & \text{or absorbed by water} & & \text{destroyed} & & \text{water to glass} \end{array}$$

The exergy balance for saline water used in the basin is shown in Figure 4.26.

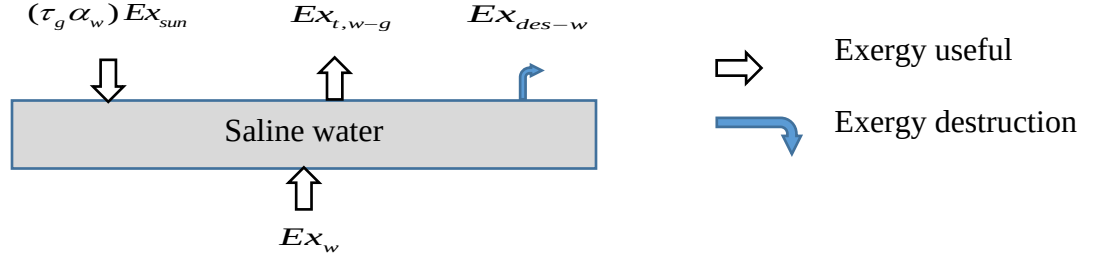


Figure 4.26: Exergy balance of a saline water

Exergy balance for saline water is obtained from equation (4.56a)

$$Ex_{des,w} = (\tau_g \alpha_w) Ex_{sun} + Ex_{p-w} - Ex_{t,w-g} \dots\dots\dots (4.56a)$$

Ex_{sun} and $Ex_{t,w-g}$ are estimated by using equation (4.54c) and (4.55b), respectively. Exergy heat transfer between absorber plate and saline water is given by equation (4.56b):

$$Ex_{p-w} = h_w \times A_w \times (T_p - T_w) \times \left(1 - \frac{T_a + 273}{T_p + 273}\right) \dots\dots\dots (4.56b)$$

4.11.2.3 Exergy Balance of an Absorber Plate with PCM

The exergy input for the basin is the fraction of solar exergy (Ex_{sun}) reaching on it. The useful exergy is utilized to raise the temperature of saline water (Ex_w) and a little is lost through PCM (Ex_{PCM}) and remaining is destroyed (Ex_{des-p}).

$$\begin{array}{ccccccc} \text{Exergy input} & & \text{Exergy useful} & & \text{Exergy lost from} & & \\ \text{absorbed by} & = & \text{in absorber} & + & \text{the basin to the} & + & \text{Exergy destruction by} \\ \text{basin absorber} & & \text{plate} & & \text{PCM} & & \text{absorber plate} \end{array}$$

The exergy balance for absorber plate with PCM used in the basin is shown in Figure 4.27.

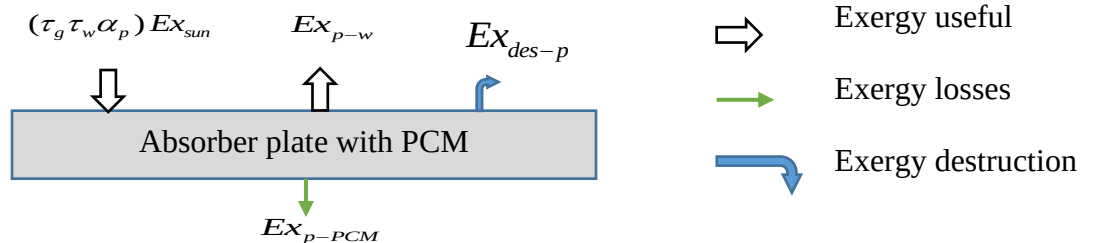


Figure 4.27: Exergy balance of an absorber plate with PCM

The exergy destructions in basin are given by following equations (Vaithilingam and Esakkimuthu, 2015): Exergy balance for the absorber plate can be written as equation (4.57a):

$$Ex_{des.,p} = (\tau_g \tau_w \alpha_p) Ex_{sun} - (Ex_{p-w} + Ex_{p-PCM}) \dots\dots\dots (4.57a)$$

The transferred exergy rate from the absorber plate to the PCM layer is found by equation (4.57b)

$$Ex_{p-PCM} = \left(\frac{K_{PCM}}{X_{PCM}} \right) A_p (T_p - T_{PCM}) \left[1 - \frac{T_a + 273}{T_p + 273} \right] \dots\dots\dots (4.57b)$$

4.11.2.4 Exergy Balance of an Absorber Plate without PCM

The exergy input for the basin is the fraction of solar exergy (Ex_{sun}) reaching on it. The useful exergy is utilized to raise the temperature of saline water (Ex_w) and a little is lost to the ambient (Ex_{loss}) and remaining is destroyed (Ex_{des-b}).

$$\begin{array}{ccccccc} \text{Exergy input} & & \text{Exergy useful} & & \text{Exergy lost from} & & \\ \text{absorbed by basin} & = & \text{in absorber} & + & \text{the basin to the} & + & \text{Exergy destruction by} \\ \text{absorber plate} & & \text{plate} & & \text{insulation} & & \text{absorber plate} \end{array}$$

The energy balance for absorber plate used in the basin is shown in Figure 4.28.

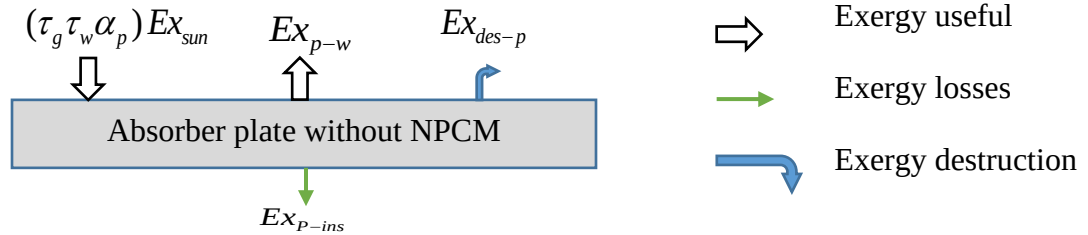


Figure 4.28: Exergy balance of an absorber plate without PCM

The exergy destructions of an absorber plate without PCM can be written as:

$$Ex_{des.,p} = (\tau_g \tau_w \alpha_p) Ex_{sun} - (Ex_{p-w} + Ex_{p-ins}) \dots\dots\dots (4.58a)$$

$Ex_{t,p-w}$ is exergy heat transfer between absorber plate and water, is given by equation (4.56b). The transferred exergy rate from the absorber plate to the insulation layer is given by

$$Ex_{p-ins} = \left(\frac{K_{ins}}{X_{ins}} \right) A_p (T_p - T_a) \left[1 - \frac{T_a + 273}{T_p + 273} \right] \dots\dots\dots (4.58b)$$

4.11.2.5 Exergy Efficiency

The exergy efficiency of the solar still is defined as the ratio of the evaporative exergy to the net input sun exergy. It can be written as (Shoeibi *et al.*, 2021; Yousef *et al.*, 2019):

$$\eta_{ex} = \frac{\sum Ex_{out}}{\sum Ex_{in}} = \frac{\sum Ex_{evap}}{\sum Ex_{sun}} \dots\dots\dots(4.59)$$

The exergy input (Ex_{sun}) and exergy output (Ex_{evap}) of the solar desalination is obtained from equation (4.54c) and (4.54e), respectively.

4.12 Numerical Solution and Procedure

In this section, numerical simulation of the solar still is developed by solving energy and exergy balance equation which would be in the form of partial differential equations under suitable initial conditions. The energy balance equation is solved by using finite difference method to evaluate the absorber plate, water, glass and PCM temperature in the still. Numerical calculations are made using meteorological parameters for a typical May Day under Fantale. The energy, exergy and mass balance equations are numerically solved using Microsoft Excel 2021 package.

4.12.1 Methodology for Solving the Equations

The performance of the solar still is theoretical evaluated by solving the heat balance equations of temperature and exergy destruction found on equations (4.48d), (4.49e), (4.50d), (4.51c), (4.52e), (4.55a), (4.56a), (4.57a), (4.58a). A few input parameters such as solar radiation, basin area, water depth, ambient temperature, and thermo-physical properties of PCM are initialized. Various internal and external heat transfer coefficients from equations (4.38) to (4.47) mentioned in section 4.9 were found using the initial values of absorber plate, saline water, PCM and glass temperatures. The initial temperature of water, plate and glass were considered according to (Sarhaddi *et al.*, 2017). The analysis was made for every 1 second time interval. Then, new values of temperatures at the end of first 1 second interval are calculated using the equations (4.48d), (4.49e), (4.50d), (4.51c) and (4.52e). The yield of freshwater obtained is found using the equation (4.53b).

The same procedure is repeated to calculate the new values of absorber plate, water, glass and PCM temperatures and production rate at the end of next 1 second interval. The iteration was continued corresponding to the actual metrological and operational data for 7 hours duration from 9.00 a.m. to 4.00 p.m. The detailed numerical simulation procedure is presented in a flow chart as shown in Figure 4.29.

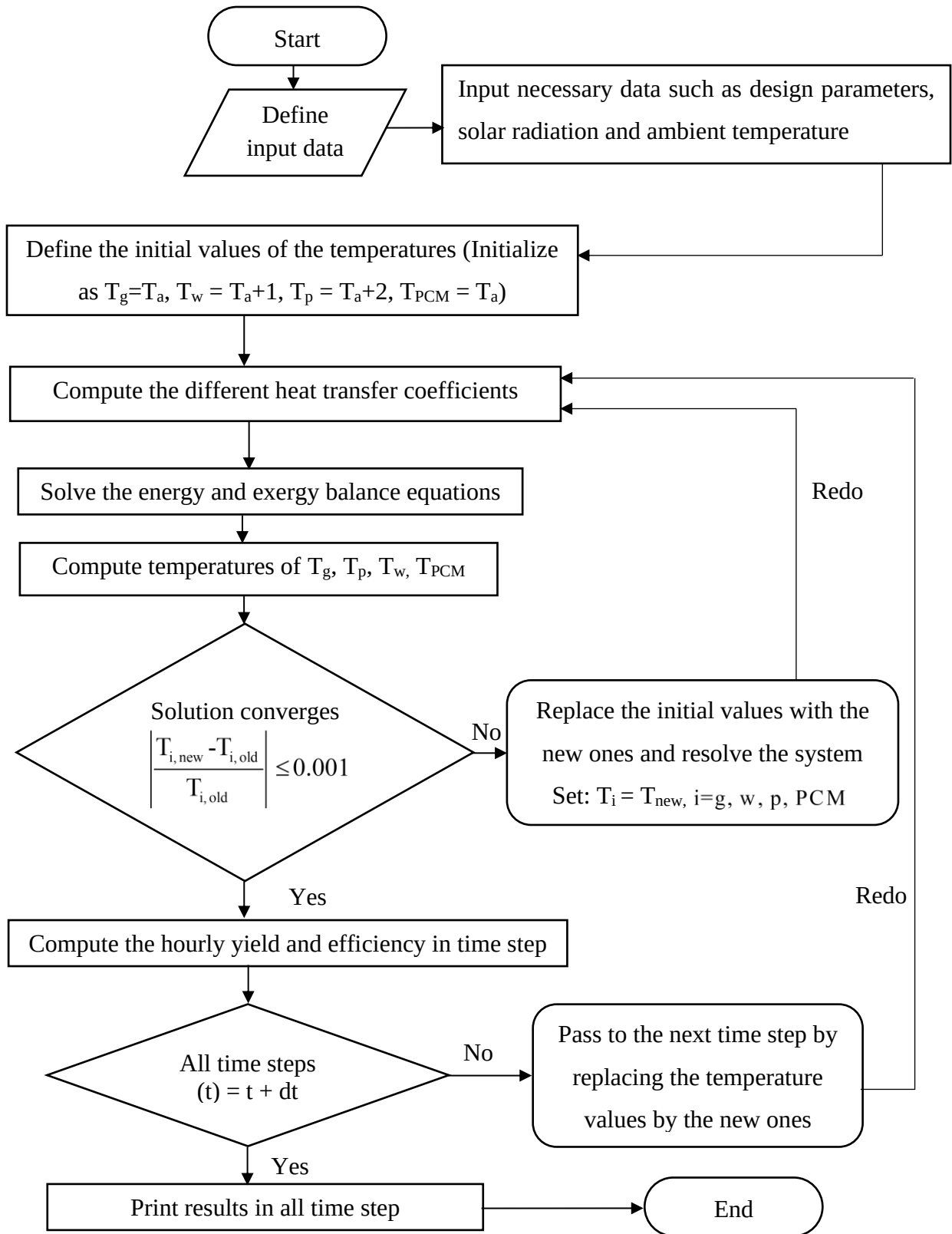


Figure 4.29: Flow-chart for theoretical analysis of a solar still

CHAPTER FIVE

EXPERIMENTAL SETUP AND PROCEDURE

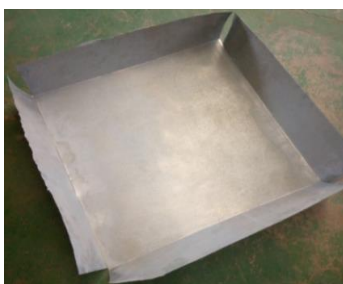
This chapter presents the detailed development process of experimental setup and experimental procedure. The development process of each component of the solar still, final assembly of the experimental setup supported with photographs and measuring devices used is also presented.

5.1 Fabrication Process

The materials used for constructing the components of the solar still were purchased from the local market. Availability and cost of the materials in the local market were considered while selecting the materials for each component. The dimensions of the parameters were depicted in theoretical analysis of a CPSS and MPSS, that can be found in section 4.6 design analysis part.

5.1.1 Fabrication of the Basin Storage

The water storage basin of the still was constructed from galvanized steel with a dimension 1 m x 1 m x 0.15 m. Water collection segment was located on all sides of the still, shown in Figure 5.1.



(a) Storage



(b) MPSS



(c) CPSS

Figure 5.1: Manufacturing process of the basin solar still for CPSS and MPSS

5.2 Preparation of Copper Oxide Nanofluids

The copper oxide nanoparticle was procured from Alpha chemicals, Ethiopia. The procured CuO nanoparticle XRD test was conducted at the department of Material Science and Engineering, ASTU. The selected nano-powder was more reasonable in accordance with thermal conductivity and cost. Steps involved in preparation of nanofluids were shown in Figure 5.2.

The key step in the use of nanoparticles to improve the thermal conductivity of base fluids is their preparation. Nanoparticles are hydrophobic in nature, prone to agglomerate together and settle quickly. So, the surfactant sodium dodecyl benzene sulphonate was used to maintain a stable and

even suspension (Elango *et al.*, 2015). In this work, three concentrations (1, 2 and 3%) of nanoparticles were considered and tested for stability to find out the concentration which is more stable. According to the numerical analysis performed and literature survey, the weight concentrations less than 3% possesses good stability and thermal conductivity (Mahian *et al.*, 2017). The prepared samples were stirred by magnetic stirrer for 30 minutes to avoid the agglomeration of nanoparticles (Manoj *et al.*, 2021). And also sonicated for 1 hour by means ultrasonicator for even distribution of particle in fluid base and better stability (Thakur and Gaur, 2021; Panchal *et al.*, 2019).

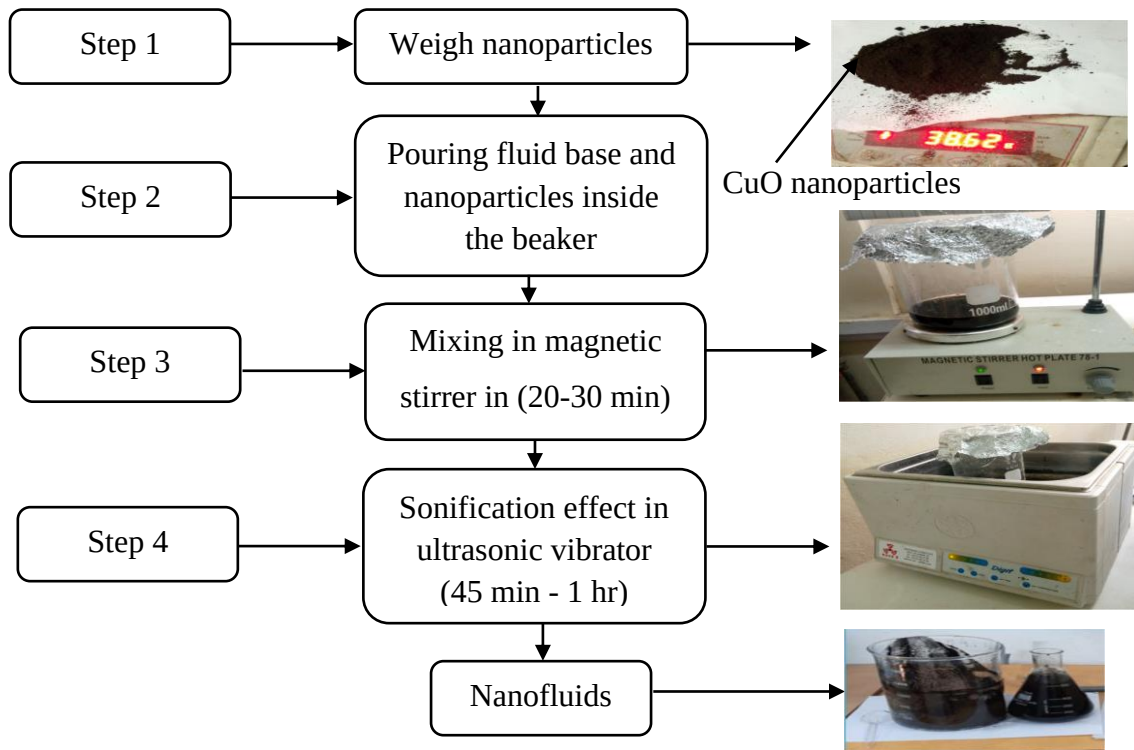


Figure 5.2: Steps and equipment's incorporate in nanofluids preparation

5.3 Experimental Set-up

The analyzes were conducted with two distinct pyramid solar stills: one is a MPSS with a unique combination of effective modifications, and the other is a CPSS that serves as the reference case.

5.3.1 Conventional Pyramid Solar Still

This arrangement consists of an absorbing plate with an insulator and a glass cover to trap the solar radiations inside the still. Absorber plate of the dimension 1 m x 1 m is fabricated from galvanized sheet, then coated with the black paint so as to increase the heat absorbing capacity of the absorber.

The glass cover was installed at the height of 0.3 m from the absorber plate. Transparent glass with the thickness of about 4 mm is used to cover the upper surface of the still. The glass is kept at the inclined angle of 30° , those four sides so as to form the slope like structure at the all sides. Hence this is called as square pyramid shaped solar still. The sloping of the glass aids in the effective collection of the condensed water. Provision for sending in saline water and collecting pure water was setup with pipes running down the saline storage tank. Insulation of the still was made with the glass wool and wood material of thickness 0.05 m and 0.02 m, respectively, so as to avoid the escape of the trapped radiations from the still. The experimental setup of the CPSS considered for the analysis and observation was shown in the Figure 5.3.



Figure 5.3: Experimental setup of the conventional pyramid solar still

5.3.2 Modified Pyramid Solar Still

As proposed, the modified solar still have a unique combination of impactful modifications such as v-corrugated absorber surface, coating the absorber surface with CuO nano black paint, nano-embodied PCM and internal reflective mirrors. Glass wool with a thickness of 5 cm was covered along the outer boundary of the MPSS which act as predominant thermal insulators which on prolonged time induce the circulation of thermal energy within the basin system itself.

The transparent glass cover of 4 mm thickness, served as solar energy transmitter as well as a condensing surface for the water vapors generated in the basin of the still. Also, the glass solar still interface was completely sealed with silicon to arrive at a leak-proof system. The basin is constructed in the form of v-corrugated absorber surface made up of galvanized iron with the dimension of 1 m x 1 m and is mounted on a basin structure present in the still. The proposed basin was covered with blend of CuO nanoparticles and black paint so that the thermal conductivity of black paint increase.

5.3.2.1 Nano-coating of the Absorber Plate

The black enamel paint was purchased from local market. Once the process of converting nanoparticles to nanofluid is completed (section 5.2), the very next step is the blending with black enamel paint. First, the 118.24% weight concentrations of CuO nanoparticles means using 118.24-g nanomaterial was converted into nanofluid. Then, the prepared nanofluid mixed in 0.5 kg of black chrome paint. Magnetic stirring produced a uniformly distributed mixture of nanoparticles and black enamel paint.



CuO Nanoparticle



Powder of CuO NPs



Black paint

Figure 5.4: Copper oxide nanoparticles and black paint procured from market

5.3.2.2 Energy Storage

Moreover, for accurate prediction of the effect of blend materials in the paint, the losses occurring in the solar still have to be minimized. The paraffin wax was designated as a PCM. The basin of solar still was filled with 22 kg paraffin wax to store the heat and placed beneath the v-corrugated absorber to extend the distillate time after sunset. The paraffin wax modules were first crushed into smaller pieces and melted using fire. CuO nanoparticle was used as a thermal conductivity enhancer for paraffin wax.

Similar to the nano-coating, once the process of converting nanoparticles to nanofluid is completed (section 5.2), the very next step is the blending with PCM. Three weight percentage of CuO nanoparticles were designated to form PCM nanocomposite. Based on the recommendations from (Rufuss *et al.*, 2016) regarding the preparation of nano-composites, the paraffin wax were heated to above the melting point by a fire, and then an anionic surfactant, SDBS (sodium dodecylbenzene sulfonate) was added to the PCM with the mass ratio of SDBS to nanoparticle of 1:1. The purpose of the surfactant was to ensure stability and homogenous dispersion of the nanoparticles. The mixtures were then sonicated for 1 hours at 40 kHz. Thus, aggregation and settling of nanoparticles in the PCM was avoided. After that, fire was used to keep the PCM in liquid state. Finally, the PCM poured into the v-corrugated absorber under the basin, depicted in Figure 5.5.



Figure 5.5: PCM filling process

Moreover, to maximize the intensity solar rays, internal reflective mirrors with dimensions of 1 m x 0.15 m were attached to the inner sidewalls of basin. A distillate output channel was provided at the end of the basin for the collection of distillate output, a hole was drilled in the channel and plastic pipe was fixed through it with an adhesive silicon. A photographic view of the proposed experimental setup of the modified solar still used for the production of desalinated water from saline water was shown in the Figure 5.6.



Figure 5.6: Experimental setup of the modified pyramid solar still

5.4 Location of the Test

The potential availability of solar radiation at Fantale is more suitable for solar still applications. However, the fabricated solar still test and process of the experimentation was carried out under Adama's climatic conditions. Since, Fantale Woreda is far away from Adama and it is almost 100 km from Adama town. Transportation of the setup is the most basic problems raised. Solar radiation values of these two areas: Adama (Latitude 8.558° N and Longitude 39.28° E) and Fantale (latitude 8.983° N, and longitude: 39.93° E) were nearly similar, this implies performance analysis of testing in Adama town doesn't matters. These two-region geographic location shows that the region was semi-arid (Adama) and very hot (Fantale) climate condition. After estimation of solar radiation for Adama and Fantale the experimental testing taken account in Adama town and it also works for Fantale since solar radiation value nearly similar.

5.5 Experimental Procedure

The experimental setup with necessary instrumentation was developed and tested its performance during May months of 2022 with modified and conventional solar still. To start the experimental analysis, a sample of saline water from Lake Basaka was poured into the basin of the solar still. Then, the temperature of the saline water on the basin start to rise; as the temperature rises the distillation was begun. The water was evaporated on the glass cover at the top of the solar distiller.

When the steam evaporates on the glass, it was condensed. Due to the gravity or edge of the inclined glass cover, the condensed water was accumulated on the water collection segment, and then transported to the water tank with the aid of pipes. The distillate output from the passive solar still determines which of the two solar distillers, either conventional or modified solar still is more effective and productive. The amount of water poured into the solar distiller was compared with its yield. During the experimental period to further verify the experimentation several changing variables was considered (section 5.7) and several instruments were used (section 5.6).

5.6 Description of the Instruments

The instruments used for the measuring of the parameters and their specifications are summarized in this section. It's crucial to record the conditions of the experiment for a better understanding of the results and to evaluate the enhancement of them. The climatic parameters (solar radiation, ambient temperature and wind) were taken from National Metrological Agency, Adama branch, Ethiopia due to the absence of measuring instruments. The most important measurement parameter was the temperatures. Temperatures of ambient, absorber plate, water, glass and energy storage were measured with the help of K-type thermocouple and thermometer. The temperature sensors were placed at important nodal points. The thermocouple was calibrated in a constant temperature bath before installing in the solar still. The detailed calibration process has been presented in Appendix D.

Table 5.1: Specifications of the measuring instrument with parameter

Parameter	Instrument	Model	Range
Temperatures	Thermocouple	K-type thermocouple	0 - 100 °C
	Thermo meter	Mercury thermometer	0 - 100 °C
Productivity	Borosilicate glass	-	0 - 1000 mL

A photographic view of the proposed experimental setup used for the production of desalinated water from saline water with necessary instrumentations were shown in the Figure 5.7.

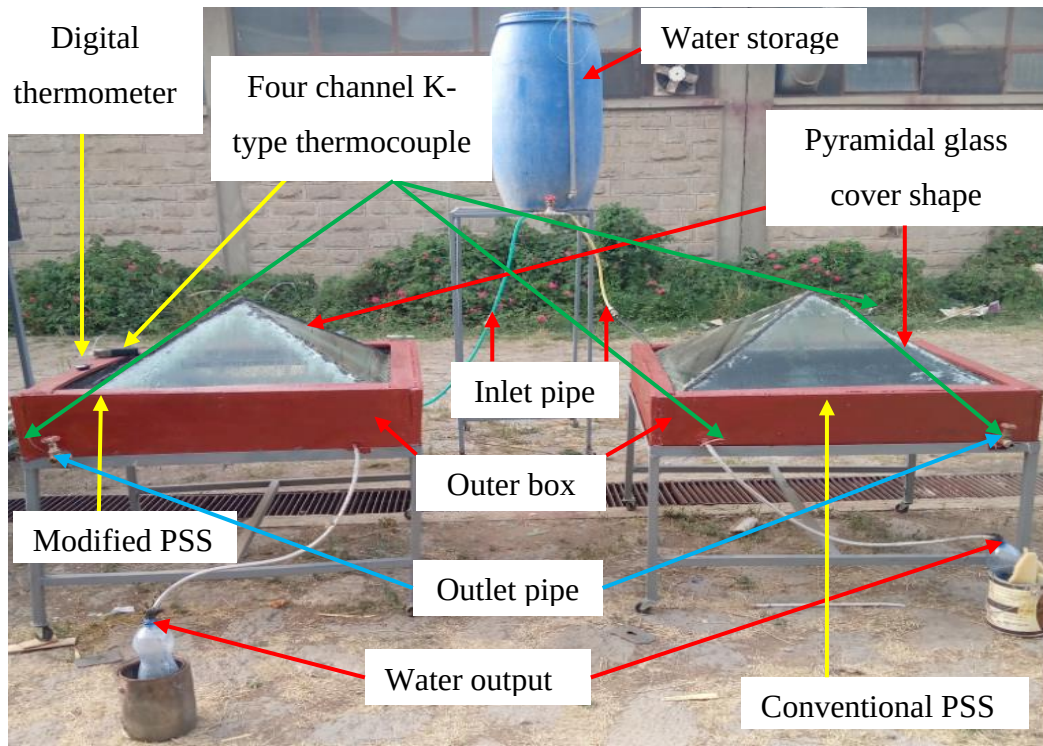


Figure 5.7: Pictorial view of experimental setup with necessary instrumentations

5.7 Experimental Analysis and Experimentation

The experiments were conducted in a month of May. The estimated duration of the experiment in a day is 8 hours which is scheduled between the 3:00 a.m. and 5:00 p.m. As the incident radiation is not same or certain on all the days sets of results were observed on different days and a fair comparison was done to find the most suitable period for the good incident radiations. For the effective trapping of solar radiation from the sun, the still was placed in the optimum a manner.

5.7.1 Experiments Conducted

This sub-section briefly discusses about the parameters and experimentation conducted to enhance the yield of solar stills.

5.7.1.1 Varying Depth of the Water

Series of tests were done by varying the depth of the water levels (1, 2 and 3 cm or 10, 20, and 30 Liters) and the observations were recorded. The yield obtained from conventional and modified

pyramid solar still with different modes of the water depth was compared to analyze the best optimum parameters. The temperature of ambient, water, absorber plate, glass cover, phase change materials and hourly water generation were recorded.

5.7.1.2 Impacts of Proposed Modifications

The effect of proposed modifications (such as v-corrugated absorber, CuO nano-coating, internal reflectors and nano-enhanced phase change material) was examined experimentally and compared with the conventional that serves as the reference case. To increase the surface area of evaporation subjected to solar radiation use of v-corrugated absorber was analyzed. To increase the rate of solar insolation and absorptivity inclusion CuO nanocoated on the absorber plate was examined. Enclosure of nano-embodied phase change material which is used as energy storing materials was examined. Use of internal reflector reduce heat loss from sides of solar stills.

5.7.1.3 Varying Concentrations of CuO Nanoparticles

For this study three different volume concentration ratios (1, 2 and 3%) of CuO nanoparticles were considered for analysis. Depending on numerical analysis and literature survey, 3% volume concentration of CuO nanoparticle was designed, for nanocoating of absorber plate and nano-embodied phase change material.

5.8 Experimental Uncertainty Analysis

Experimental uncertainty always exists as a result of the measuring method, observation process, environmental conditions, calibration and error in measuring instruments. The external uncertainty is mainly associated with the measuring instruments used during the experiment. The temperatures stated at typical locations in earlier section and yield of solar still was measured experimentally. This instrument uncertainty can affect the accuracy of the measured results. The associated percentage errors, accuracies, and ranges of instruments were summarized in Appendix E.

CHAPTER SIX

RESULTS AND DISCUSSIONS

In this chapter, the theoretical and experimental results obtained from the designed solar still is presented. Verification and validation of the theoretical analysis is performed by comparing the predicted results with the experimental data. Energy and exergy performance of conventional and pyramid solar still, and essential points that arise from the results are discussed in detail. Finally, the water quality and economic analysis of the solar still is presented.

6.1 Variations in the Intensity of the Solar Radiation with Time

The experiments were conducted for seven consecutive days (15 - 21, May 2022), starting from 9:00 to 17:00 hours when the intensity of the radiation was very fair and not much varied. The estimated monthly average hourly incident solar radiation on a tilted surface of a May month corresponding to the local time was tabulated and plotted as graph which was shown in Figure 6.1.

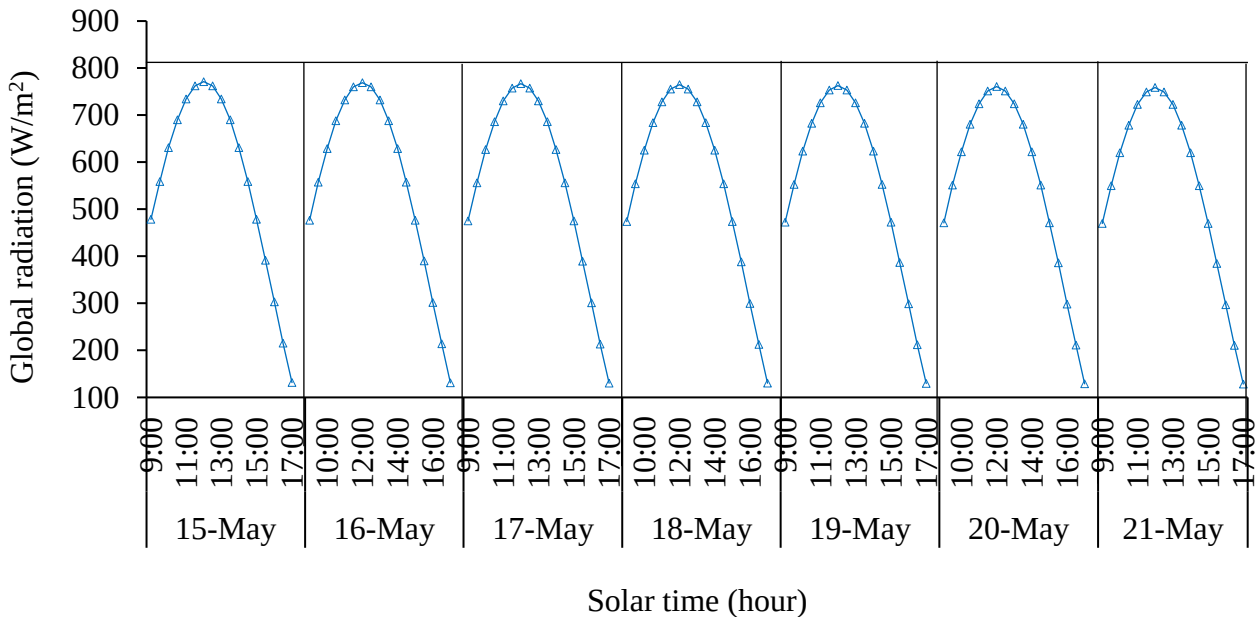


Figure 6.1: Estimated solar radiation of Adama's climatic condition in May month

The observed average maximum and minimum intensity of the solar radiation were reached 770 and 300 W/m^2 at 12:00 and 16:00 hour, respectively, with an average of 450 W/m^2 . Here, the solar radiation reaches maximum value of 770 W/m^2 at 12:00 hour. The sky was clear and there was no freeze during the experimental days.

6.2 Ambient Temperature Profile

The variations in average ambient temperature with respect to local time during theoretical analysis with the months of May were shown in Figure 6.2.

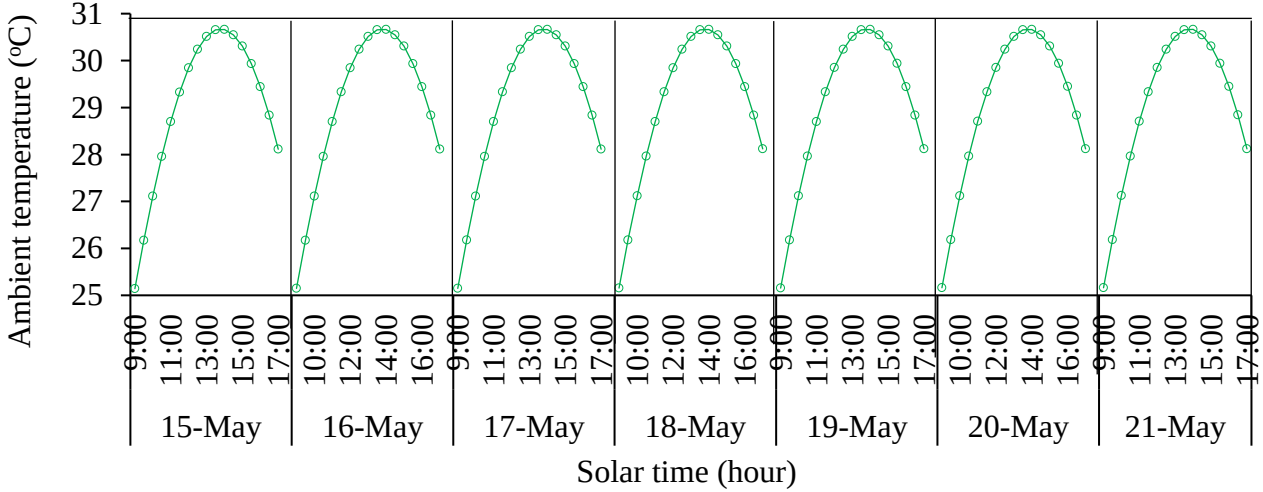


Figure 6.2: Variation of ambient temperature with solar time in May month

Here, the ambient air temperature was in the range of 25.1 and 30.7 °C with an average of 27.9 °C. The atmospheric temperature reaches the maximum value of 30.7 °C at 14:00 hour. Experimental results of the days with average atmospheric conditions have been considered for analysis.

6.3 Experimental Observations of Pyramid Solar Still

A series of experimental observations have been made on solar stills with the use of CPSS and MPSS. Extensive experimental trials have been made for the period of 7 days to study the transient behavior of the solar still. The performances of a solar still observed during the clear sunny day with minimum fluctuations in solar radiation were considered for discussion and performance comparison. Experimental value such as temperature at typical locations of solar still, hourly yield and cumulative yield of a solar still has been described and discussed in the following sub-sections.

6.3.1 Varying the Levels of the Water

The experimental analysis of conventional and modified pyramid solar still was carried out at different depth levels of the water. The various results obtained during experimentations were recorded in a 30-minute interval. The parameters like intensity of radiation calculated theoretically due to absence measuring instruments, temperature of ambient, glass, absorber plates, water, and the corresponding yield were measured and noted for the reference in the Appendix-C.

6.3.1.1 Variation of Ambient Temperature

The ambient temperature influences the convection and radiation losses from the top surfaces. And also, influences the conduction losses through the insulation material packed at the bottom surface of the solar still. Moreover, the ambient temperature affects the yield of solar still. The ambient temperature variations observed during experimentation was shown in Figure 6.3. It is observed that, the ambient temperature was varied from about 25.3 to 34.8 °C during the experimental observations. The sky was clear and there was no freeze during the experimental days. It is also observed that, the ambient temperature is almost same for all the experimental days and conditions.

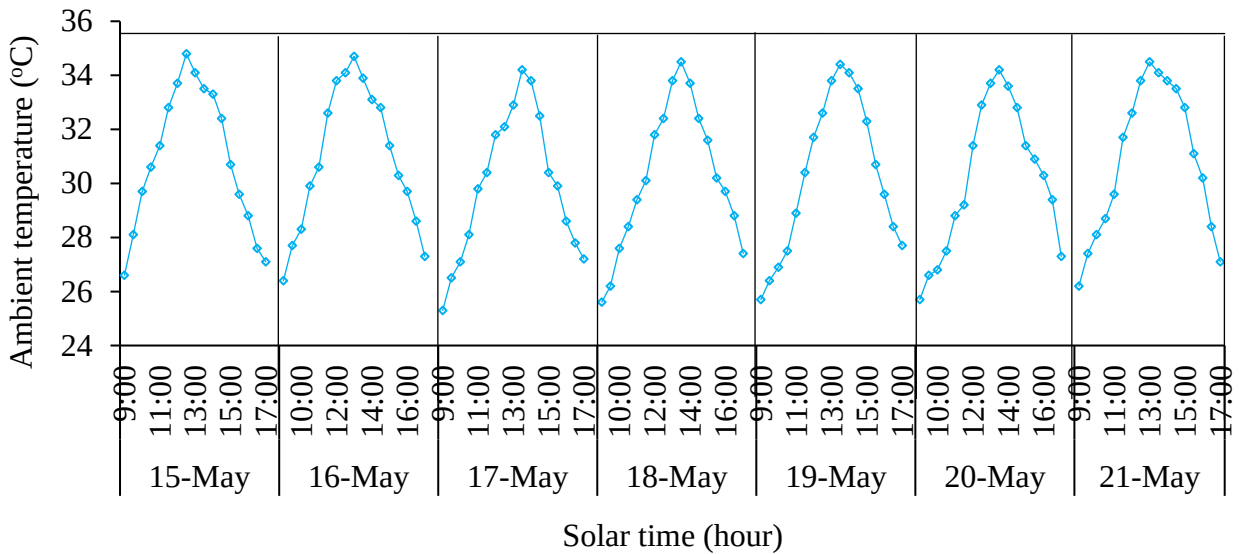


Figure 6.3: Variations of ambient temperatures observed during experimentation

The maximum difference in ambient temperatures observed during experimentation through different modes of operations was found to be within ± 0.5 °C.

6.3.1.2 Hourly Variation of Absorber Plate Temperatures

The hourly variations of absorber plate temperatures observed during experimental analysis of CPSS and MPSS at (1, 2, and 3 cm water depth) were shown in Figure 6.4 and Figure 6.5, respectively. It is observed that, for 1 cm water depth the absorber plate temperatures of CPSS were increased from about 32 to 64 °C with increase in solar irradiation during morning hours till 12:30 hours. After 12:30 hours, the absorber plate has attained steady state till 14:30 hours. After 14:30 hours, the temperatures in the basin gets reduced in the afternoon hours. For 3 cm water depth, the temperatures of CPSS were increased from about 28 to 61 °C till 13:30 hours.

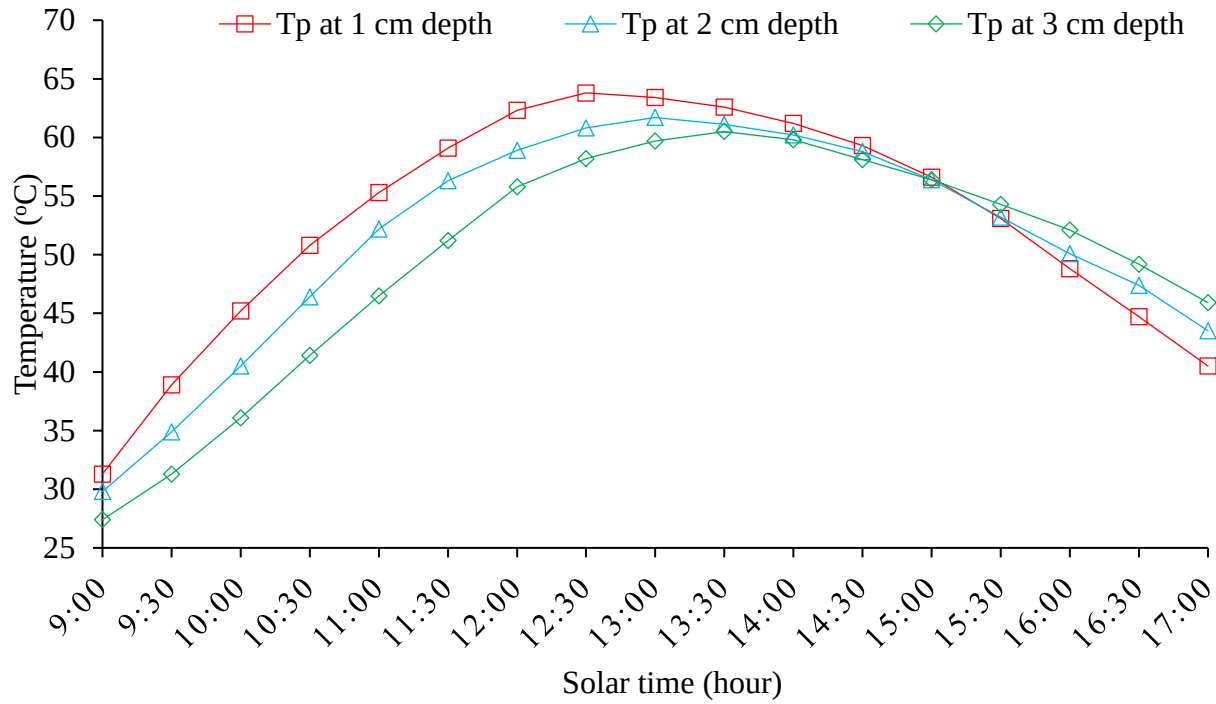


Figure 6.4: Hourly variations of absorber plate temperature with CPSS

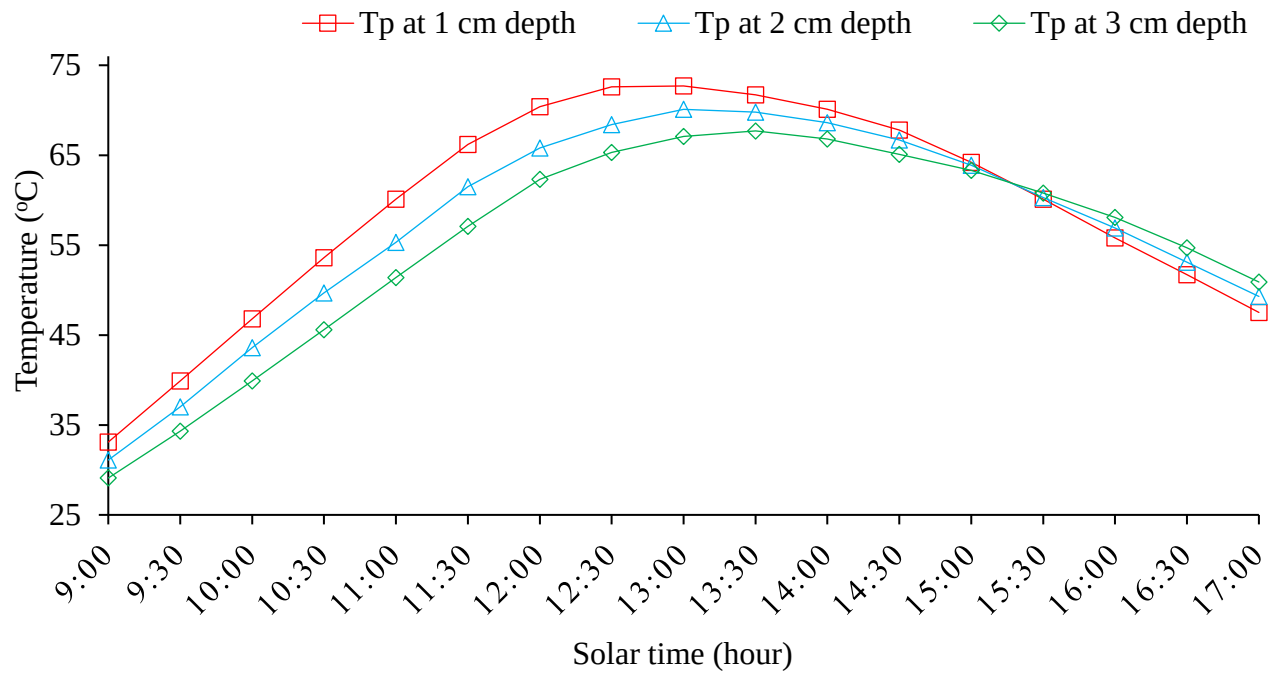


Figure 6.5: Hourly variations of absorber plate temperature with MPSS

For 1 cm water depth, the absorber plate temperatures of MPSS were increased from about 33 to 73 °C with increase in solar irradiation till 13:00 hours. In the morning, the absorber plate temperature of CPSS was observed to be higher when compared to the absorber plate temperature

with MPSS. The NPCM has capability of absorbing the heat during forenoon hours. Once the basin has reached steady state (after 14:30 hours), the temperature of basin without modifications falls down rapidly. However, the solar still with proposed modifications has controlled the temperature drop in the afternoon hours and maintain higher temperature in the basin. For 3 cm water depth, the temperatures of MPSS were increased from about 29 to 68 °C till 13:30 hours.

It is clearly noticed that the lowest basin water depth attains the highest basin water temperature and it decreases with an increase of basin water depth. During, evening absorber plate temperature attained with the low basin water depth are lesser than the temperature with high basin water depth. The reason behind this may be that the water temperature is quickly rising for a lower basin water depth due to minimum volume of water and slowly rising for a higher basin water depth.

6.3.1.3 Hourly Variation of Basin Water Temperature

The hourly variations of experimental values of water temperature inside the solar still basin operating under CPSS and MPSS with different modes of water depth (1, 2, and 3 cm water depth) were compared in Figure 6.6 and Figure 6.7, respectively.

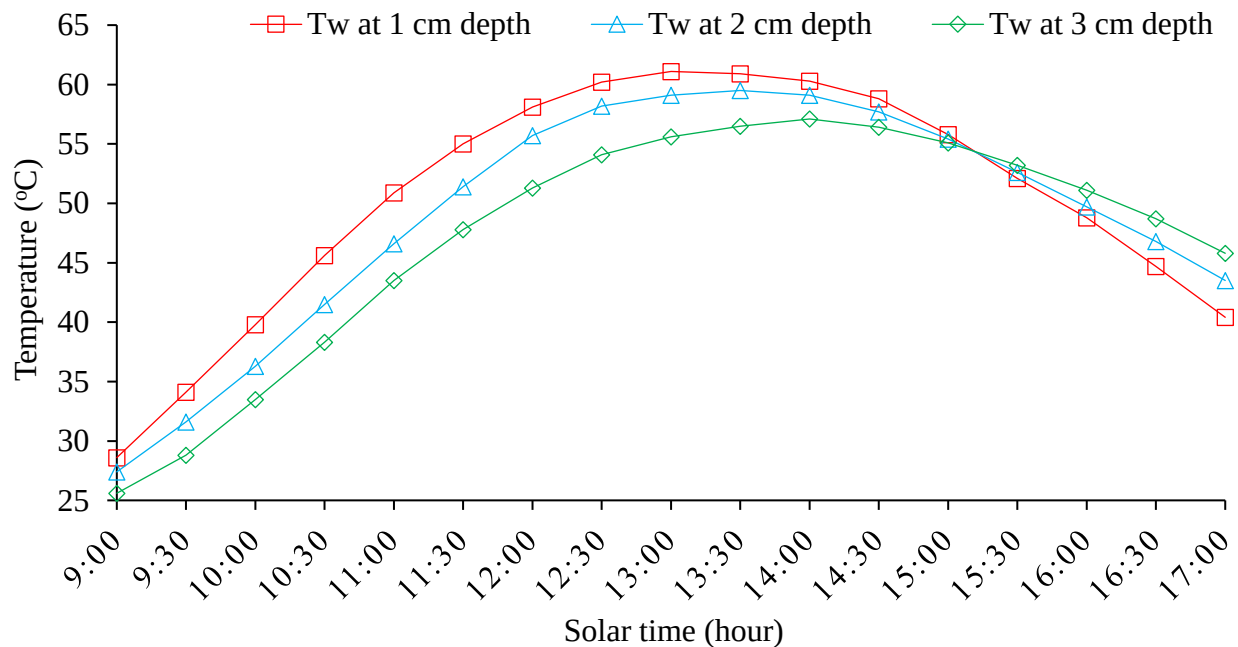


Figure 6.6: Variations of water temperatures with CPSS

It is observed that, for 1 cm water depth the water temperatures of conventional pyramid solar still in the basin were varied from 29 to 61 °C till 13:00 hours. While, for 3 cm water depth, the values of maximum basin water temperatures were ranged between 26 and 57 °C, at around 14:00 hours.

Here, the water temperature during the morning hours was less than the absorber plate temperature, whereas during the evening hours water has high temperature than the absorber plate. The higher temperature of water during the afternoon is due to the effect of the thermal inertia of water. It quickly evaporates the water during off shine period and cloudy condition.

In case of modified pyramid solar still, it is observed that, the experimental values of maximum basin water temperatures for 1 and 2 cm water depth were found at 68 and 65 °C, thru 12:30 and 13:30 hours, respectively. While, for the 3 cm water depth, the values of maximum basin water temperatures were amplified from 26 to 63 °C, at around 14:00 hours.

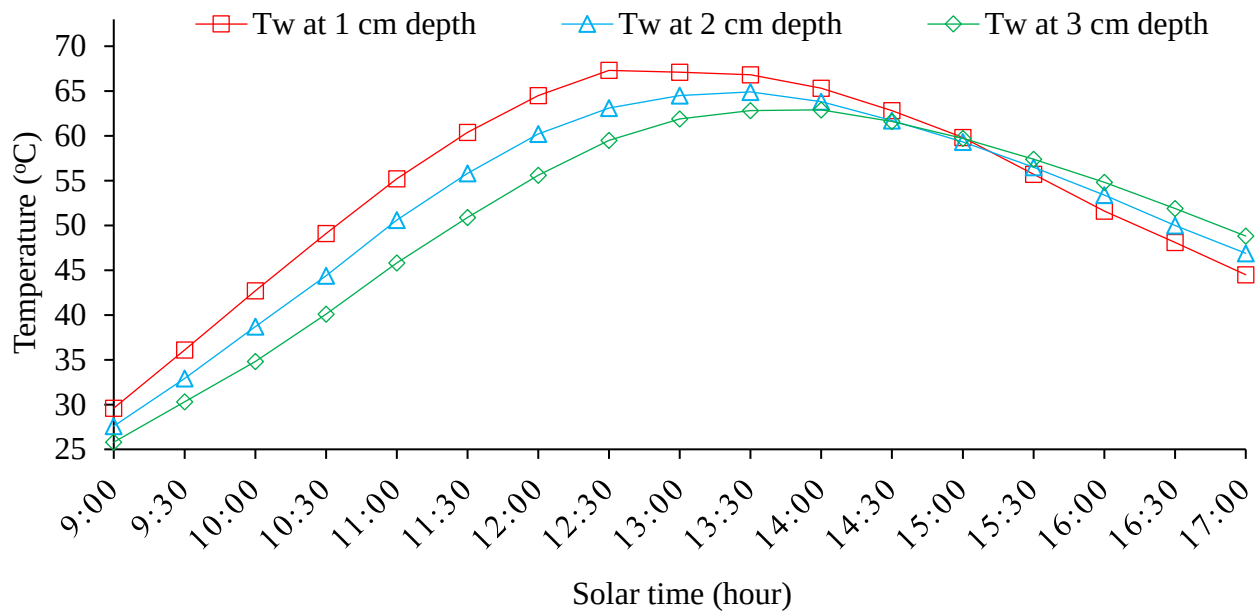


Figure 6.7: Hourly variations of water temperatures with MPSS

Hence, the temperature of water in the basin of modified pyramid solar still was found to be lower when compared to the conventional pyramid solar still during morning hours due to absorption of heat by the nano-enhanced phase change material. The nano-enhanced phase change material absorbs the latent heat released during the condensation of water vapour. However, during evening hours, the temperature of the water in the basin using nano-enhanced phase change material has released the heat and maintain higher water temperature in the basin, which enhances the yield of solar still. Though, the temperature of water in the conventional pyramid solar still was found to be lower in the evening hours and has less yield. It is observed that, the maximum value of basin water temperature decreases with an increase in the depth of basin water significantly. It is due to the high thermal inertia of higher depth of water level.

6.3.1.4 Hourly Variation of Glass Cover Temperatures

The hourly variations of glass cover temperatures during experimental analysis of CPSS and MPSS with different depth of water at (1, 2, and 3 cm water depth) were compared in Figure 6.8 and Figure 6.9, respectively. In case of conventional pyramid solar still, the maximum values of glass cover temperature of 48 °C is obtained at 13:00 hours for 1 cm depth of water, while using 3 cm depth of water, maximum glass cover temperatures of 44 °C were obtained at 14:00 hours.

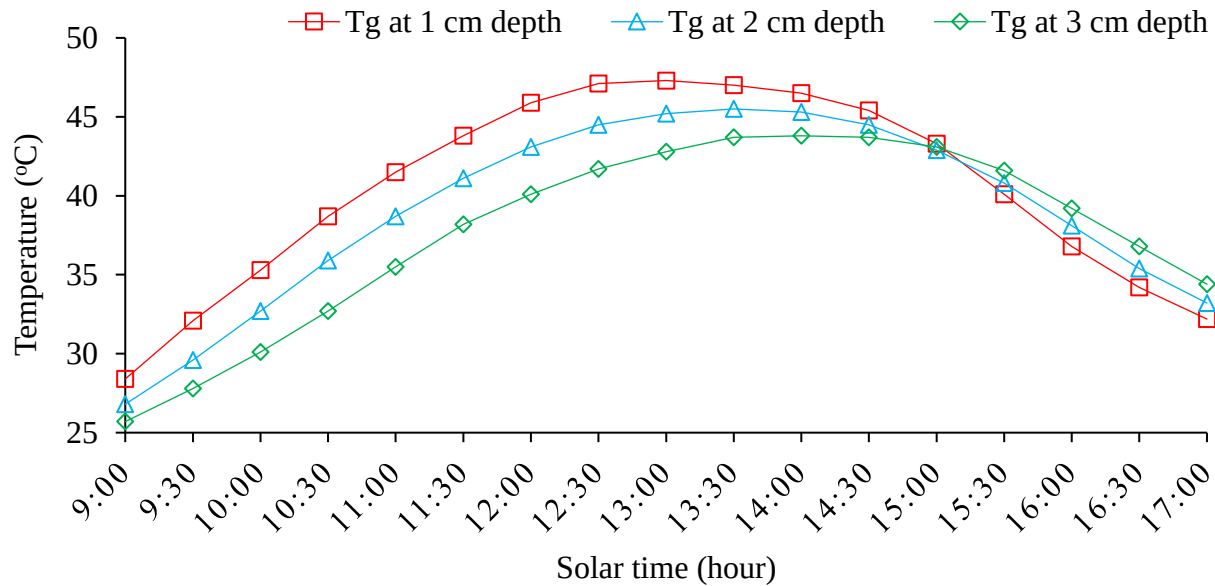


Figure 6.8: Variations of glass cover temperatures with CPSS

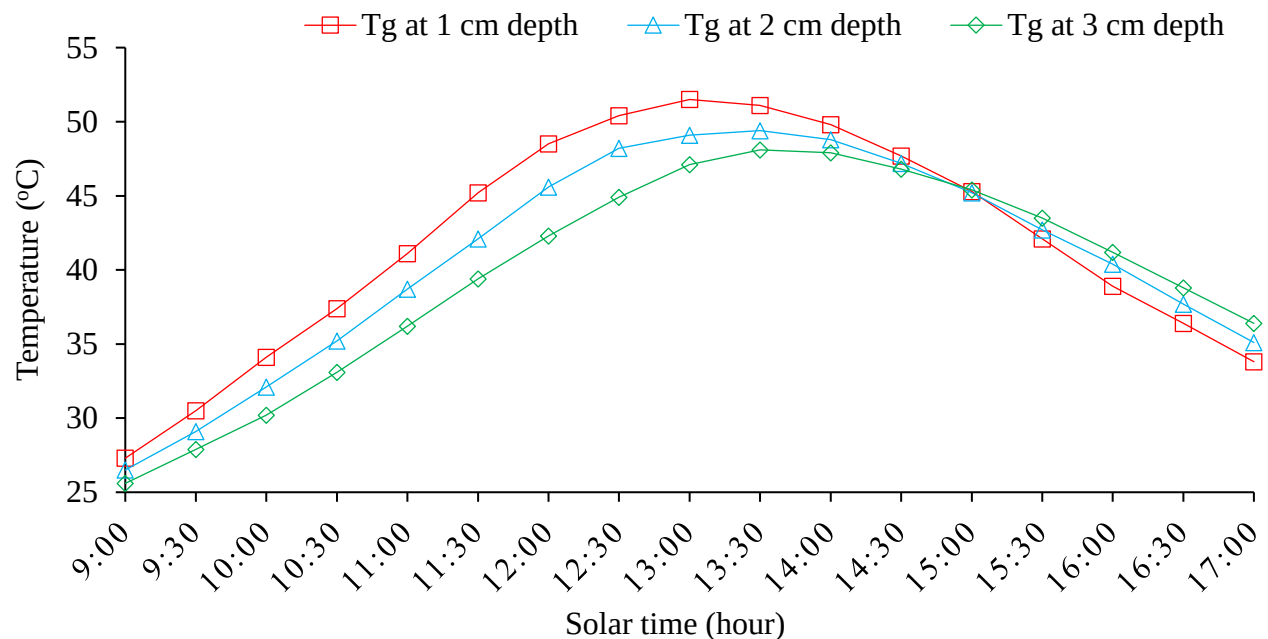


Figure 6.9: Hourly variations of glass cover temperatures with MPSS

In the case of modified pyramid solar still, the experimental values of maximum glass cover temperatures obtained is 52 °C during 13:00 hour for minimum (1 cm) basin water depth. While for the maximum basin water depth (at 2 and 3 cm), the values of maximum glass cover temperatures are 50 and 48 °C, respectively at around 13:30 hours.

The peak ambient temperature and solar radiation was observed during 13:00 and 12:00 hours, respectively. However, the glass has attained the maximum steady state temperature during 14:00 hours. During morning hours, a steep increase in glass temperature was observed till 14:00 hours. After 14:00 hours, the glass temperature falls down quickly during 17:00 hours. During, evening outer glass cover temperature attained with the low basin water depth are lesser than the temperature with high basin water depth.

6.3.1.5 Hourly Variations of Evaporation Heat Transfer Coefficients

Figure 6.10 to Figure 6.11 depicts the hourly variations of evaporative heat transfer coefficients from basin water to glass cover in CPSS and MPSS, respectively. The maximum experimental values of evaporative heat transfer coefficients are obtained as 31 and 25 W/m² °C at a water depth of 1 and 3 cm during 13:00 and 14:00 hours, respectively for CPSS. Whereas, for the MPSS, the maximum experimental values of evaporative heat transfer coefficients are found as 42 and 34 W/m² °C at a water depth of 1 and 3 cm during 12:30 and 14:00 hours, respectively.

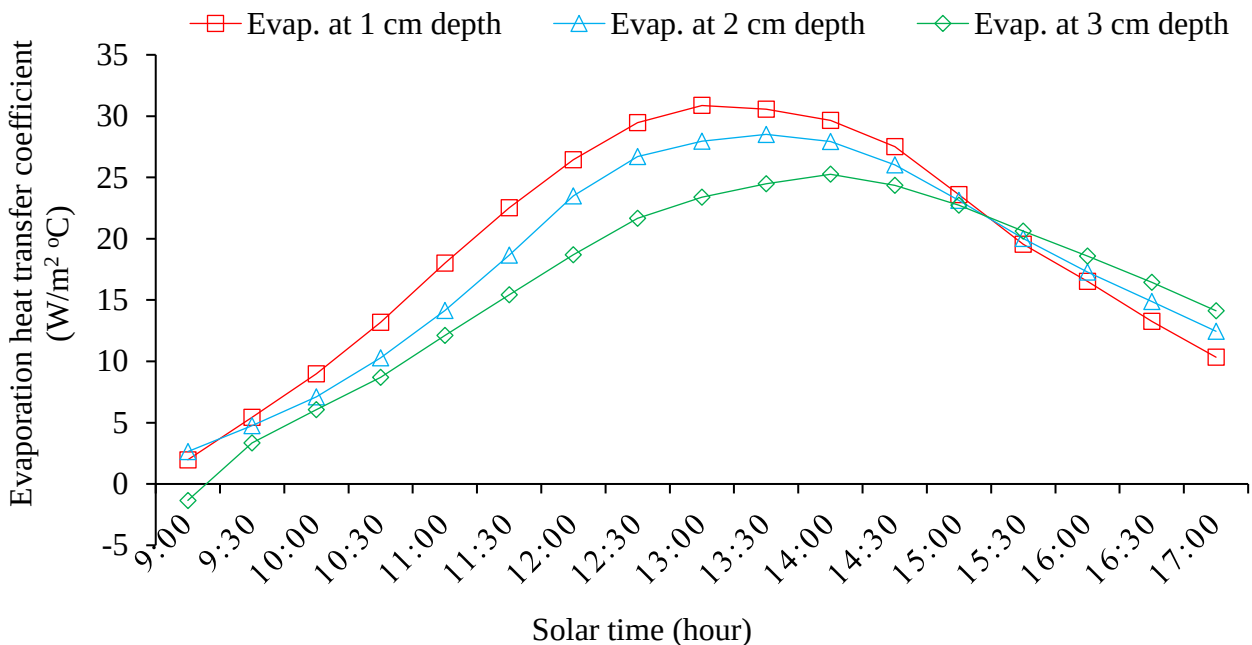


Figure 6.10: Hourly variations of evaporation heat transfer coefficients of CPSS

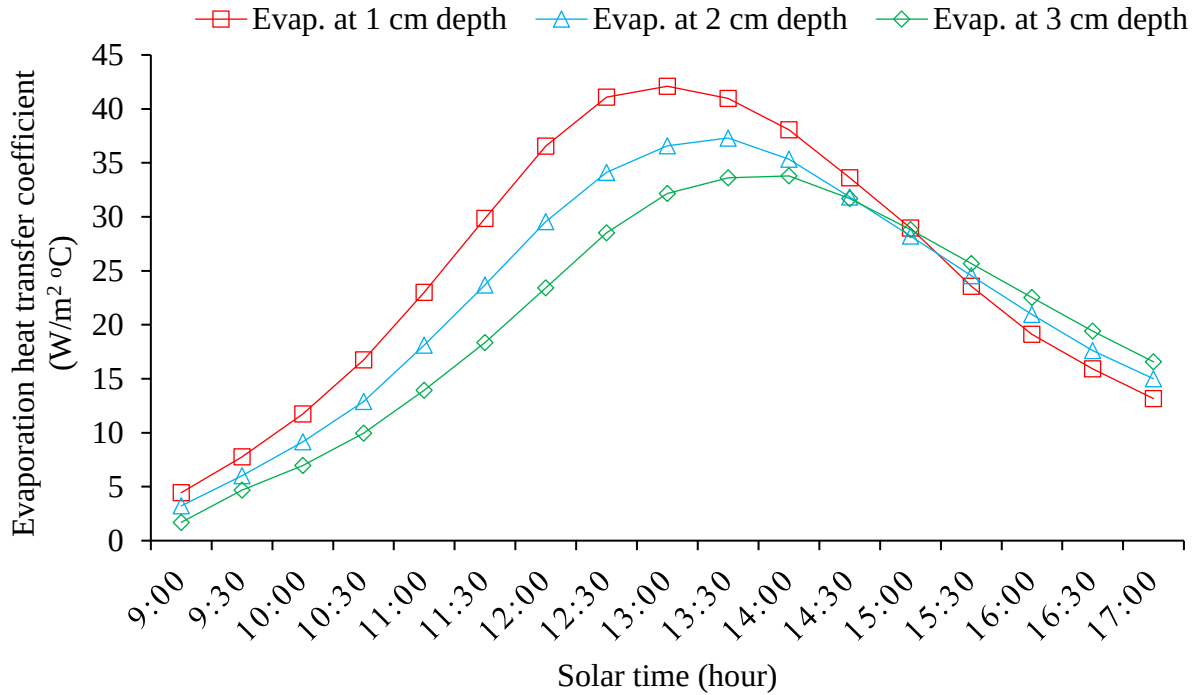


Figure 6.11: Hourly variations of evaporation heat transfer coefficients of MPSS

It is clearly observed that, the evaporative heat transfer coefficient increases with time and achieves the maximum value between 13:00 to 14:00 hour for all basin water depths from 1 to 3 cm. After 14:00 hour, its value decreases with time for both the cases of CPSS and MPSS. This corresponds to the fact that the increase in evaporation from the surface is more for increased water temperature in the basin as it acts as a driving force for evaporation. This is due to the thermal inertia of water. It is also further noted that from the experimental analysis, the values of convective and radiative heat transfer coefficients are much lesser than the value of the evaporative heat transfer coefficient.

6.3.1.6 Hourly Variation of PCM Temperatures

Here, to measure the temperature of the paraffin, two divergent vertical points in two different locations (entirely four points) were assessed (for 1 cm water depth) and the average was taken as the PCM temperature. The variations of the temperatures of PCM of MPSS shown in Figure 6.12.

It is observed that, as the solar intensity and ambient temperature increases, temperature of phase change material also increased gradually up to noon (nearly at 13:30 hour). Later, start to decline again with reducing the solar irradiation values. At the initial time of the experiment, the phase change material absorbs a thermal heat from the absorber plate of the solar still (Heating process 1), and its temperature is increased gradually. Through this process, the absorbed thermal energy

from the absorber plate is stored as a sensible heat. Later, the phase change material attained its melting point.

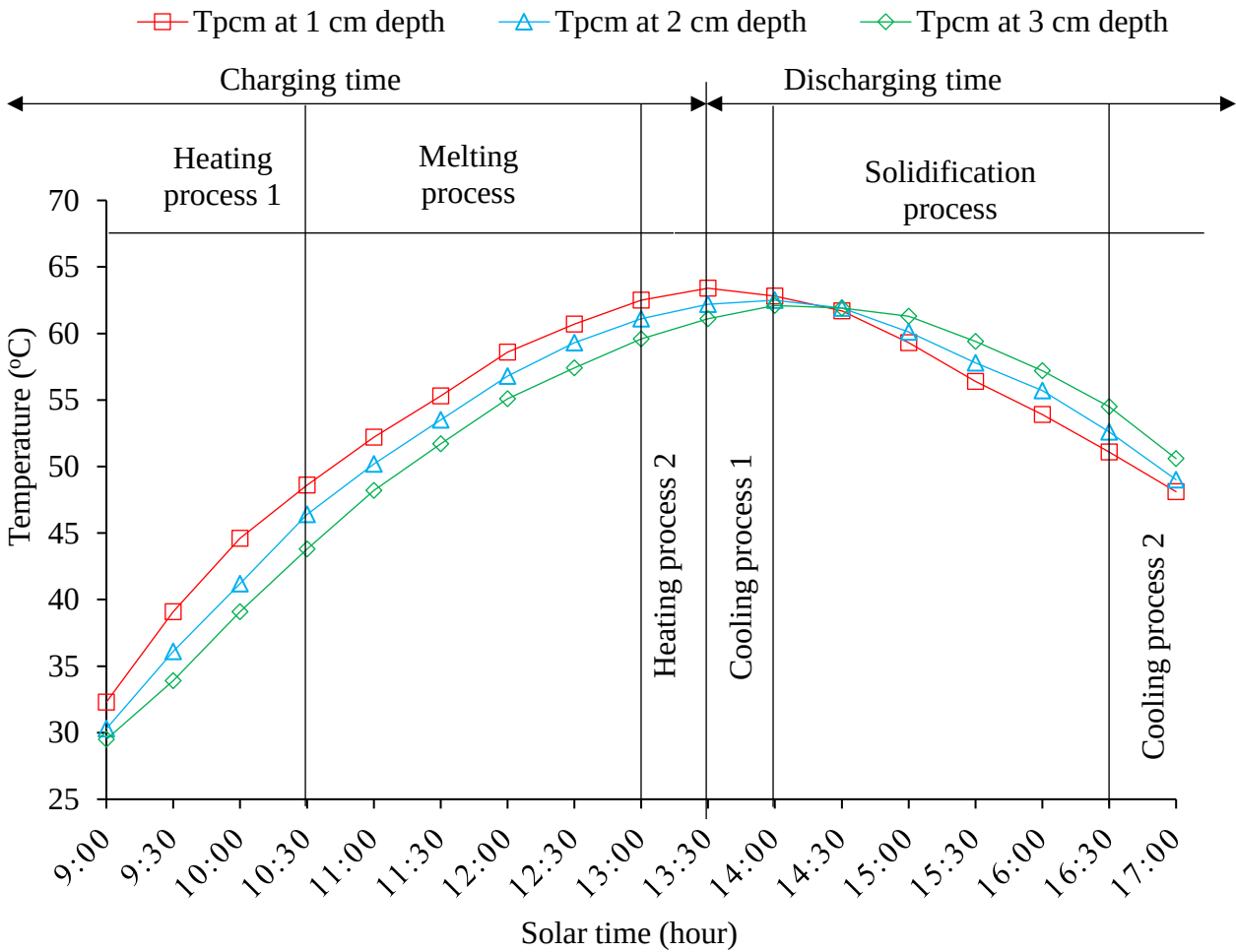


Figure 6.12: Hourly variations of PCM temperatures with MPSS

It is clearly observed that, for 1 cm of water depth, the phase change material temperature was attained melting process from 10:30 to 13:00 hour. Due to the minimum depth of water and proposed modifications, the melting process of the phase change material takes around two and half hours. This time was sufficient to melt the solid phase of the phase change material because of v-corrugated absorber and internal reflectors transfers more heat. During this process, the solid phase is altered to liquid phase. Furthermore, when the phase change material temperature attains its melting temperature, the melting process is completed (complete melting = complete phase change). Whereas, from 13:00 to 13:30 hours, where the solar radiation is highest, the charging process continues thru the zone (Heating process 2) with a clear rise in the phase change material temperature. At this phase, the phase change material temperature starts to be more than that of

the water temperature, this is because of the higher thermal conductivity of nano-embodied phase change material.

Later 13:30 hr, the temperature of PCM starts to decrease gradually as the solar radiation is decline and also due to the system heat loss. Besides, the discharging process starts with its three processes (Cooling 1 plus Solidification plus Cooling 2) as found in Figure 6.12. The temperature of the PCM is decline with time till attaining the solidification point. As it is observed, at 14:00 hour, the temperature of the phase change material starts solidification process (the process where the liquid phase is altered to solid phase). The solidification process takes more than two and half hour and this time was sufficient to solidify the liquid phase of the phase change material. After 16:30 hr, the temperature of the PCM continues declining till attaining the ambient temperature. Moreover, during the night times (discharging process), the stored heat in paraffin is released. This rises the temperature of water, as a result the temperature of phase change material declines thoroughly.

For 2 cm and 3 cm water depth, the charging process of the PCM begins with obvious increase in PCM temperature. The temperature of the PCM increases progressively and attains its melting point at 11:00 to 13:30 and 11:30 to 14:00 hour at water depth of 2 and 3 cm, respectively, this is because of the effect of basin water depth. As the solar radiation and temperature increases, as a result the temperatures of the paraffin and water also continues increasing. Later, the discharging process (heat releasing process) begins when the solar intensity starts to decline. Consequently, the temperature of paraffin also starts to decline because of releasing the heat from the PCM to the basin water. Besides, the temperature of PCM is decline with time up to achieving the solidification temperature at around 14:00 hour and the solidification rate was low. After 17:00, the temperature of the phase change material continues decline up to achieving the ambient temperature.

The utmost important observation is that the average temperatures of basin water for both CPSS and MPSS are nearly similar through the charging time, but they are dissimilar through the discharging time. This is due to the released heat from the paraffin through the discharging time which rises the water temperature of the MPSS compared to that of the CPSS (reference distiller).

6.3.1.6.1 Charging and Discharging Time of Energy Storage

The addition of nanoparticles had interesting effects on the temperature of the PCM storage units (shown in Figure 6.13 to Figure 6.15). At 1 cm water depth, the melting process of the NPCM was

higher than the other depths of water; till noontime. Then after, NPCM-1 lagged behind the other water depths in temperature. At 1 cm water depth, storage temperature increased then decreased.

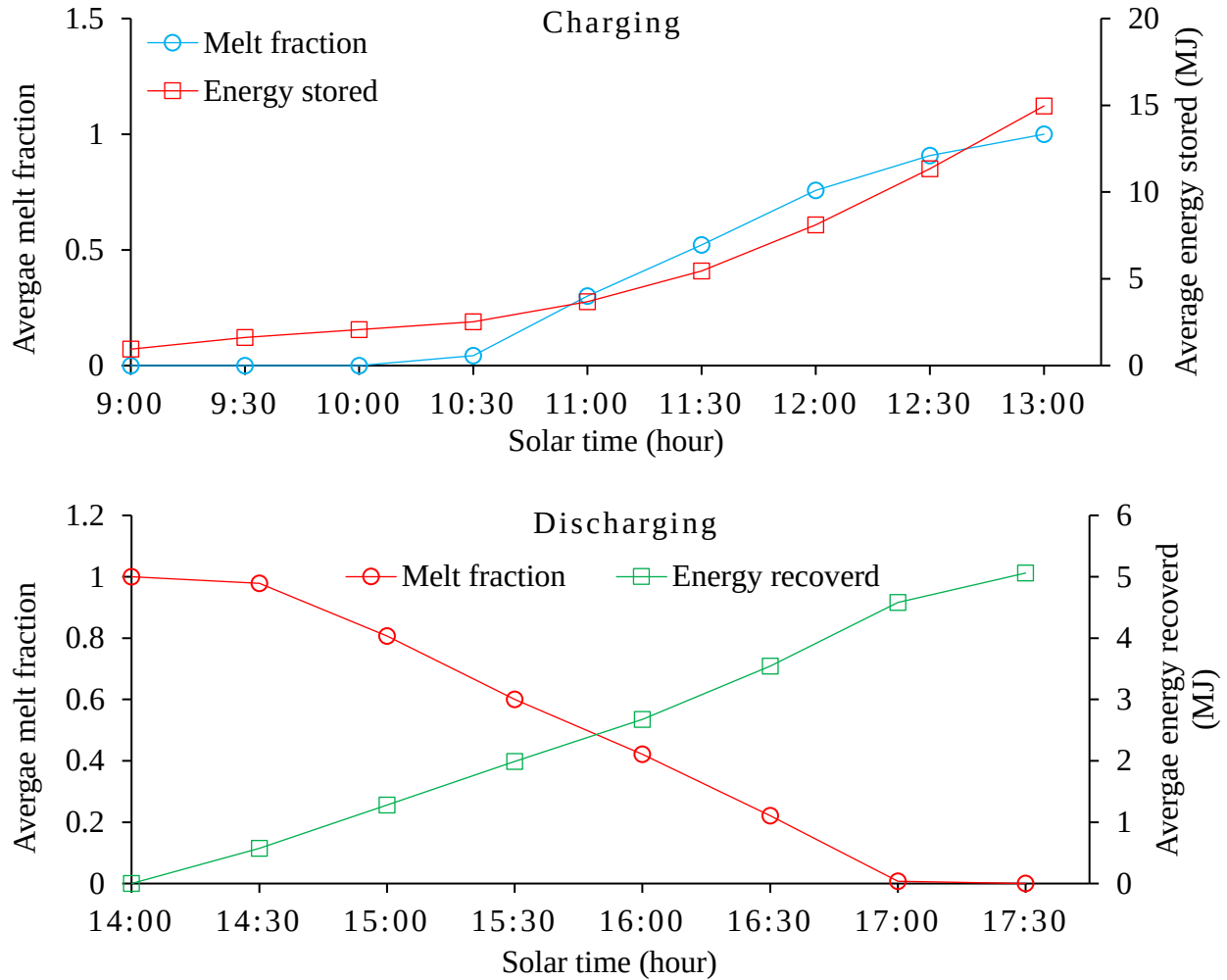
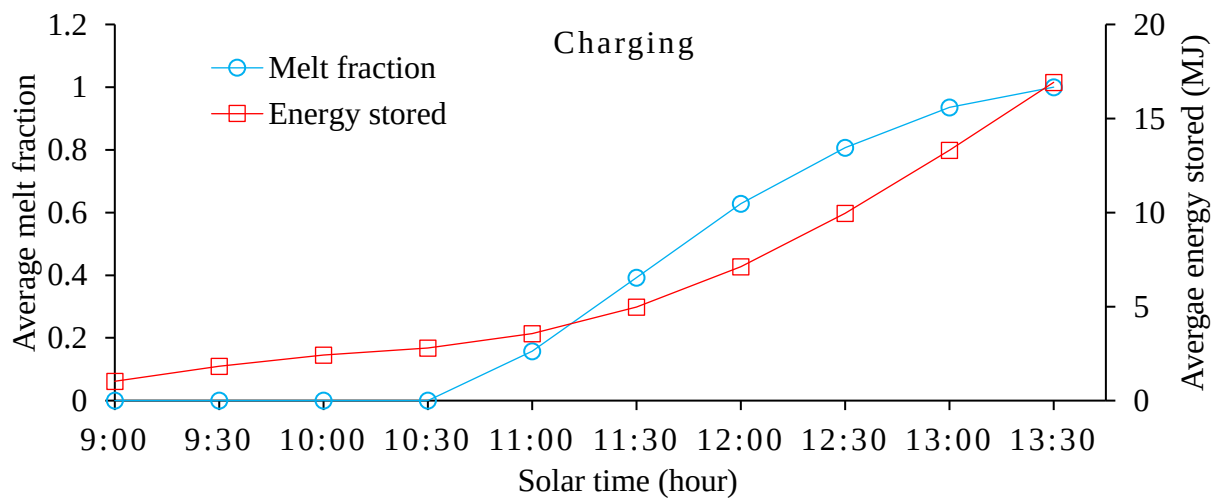


Figure 6.13: Charging and discharge time of PCM at 1 cm water depth



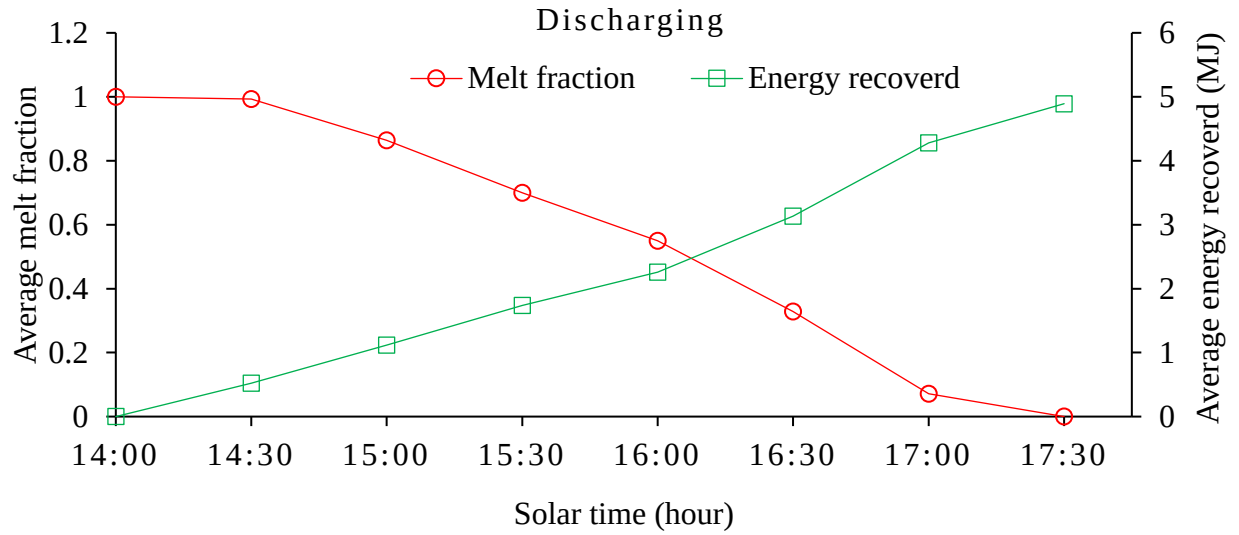


Figure 6.14: Charging and discharge time of PCM at 2 cm water depth

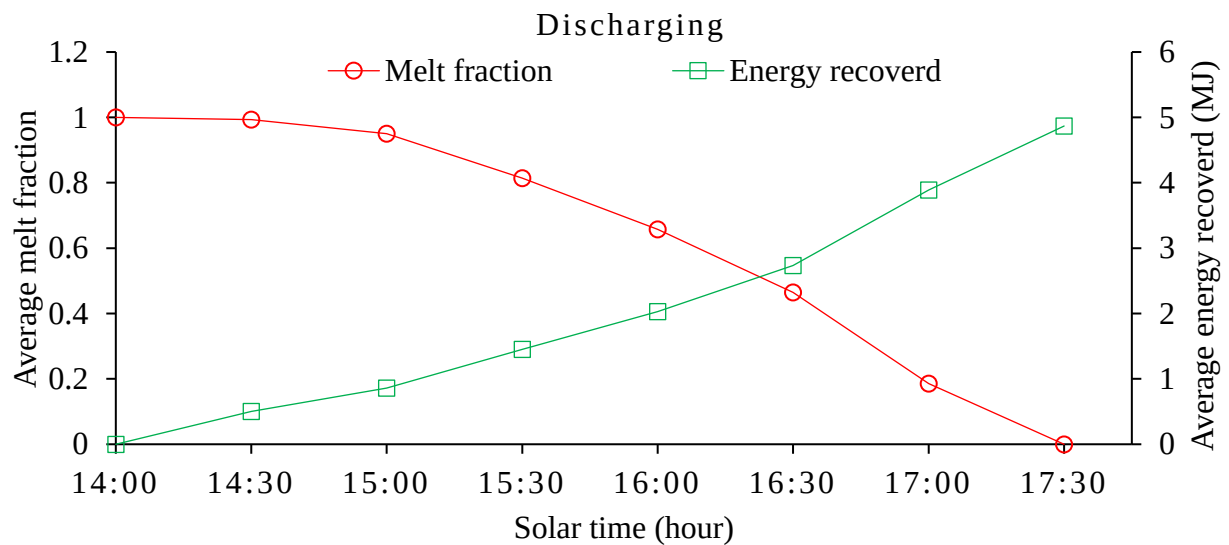
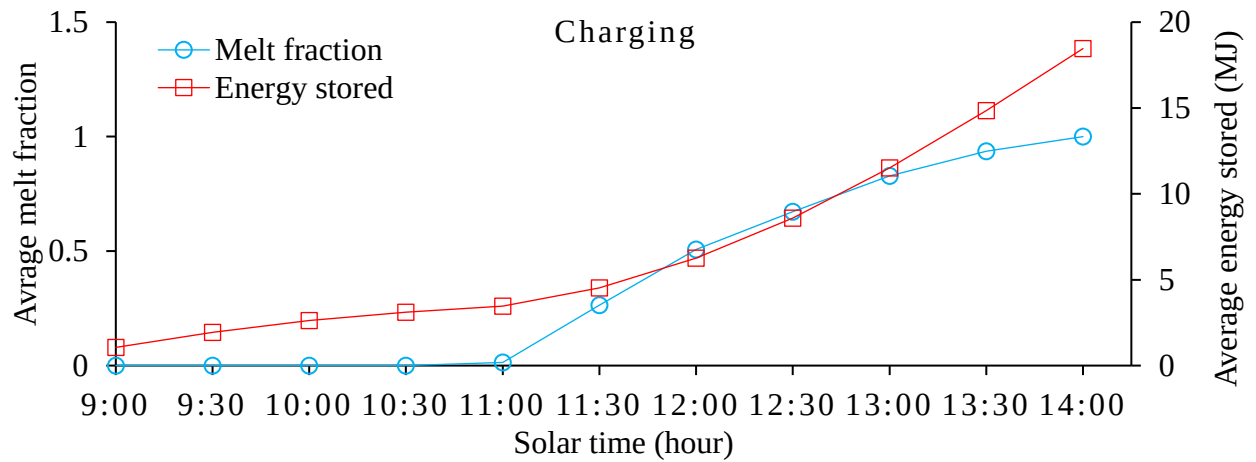


Figure 6.15: Charging and discharge time of PCM at 3 water depth

At the 3 cm depth of water, the storage unit temperature of nano-embodied phase change material was initially lower than that of the other depths of water. This was because of the maximum volume of water and it needs more time to attain maximum temperatures than other depths of water. Moreover, during discharge, the storage temperature of nano-embodied phase change material at 3 cm water depth was relatively high because of the slower solidification. During evening, among the 3 depths water NPCM-3 showed considerably better performance in storage temperature than the rest. It is due to the high thermal inertia of higher depth of water level.

6.3.1.7 Comparison of the Cumulative Yield for Different Depths of Water

Figure 6.16 and Figure 6.17 shows the cumulative yield of CPSS and MPSS during experimental observations at water depth of 1, 2 and 3 cm. For CPSS, the total cumulative yield obtained per m^2 at the depth levels of 1, 2 and 3 cm are 2.95, 2.763 and 2.443 L/m^2 day, respectively.

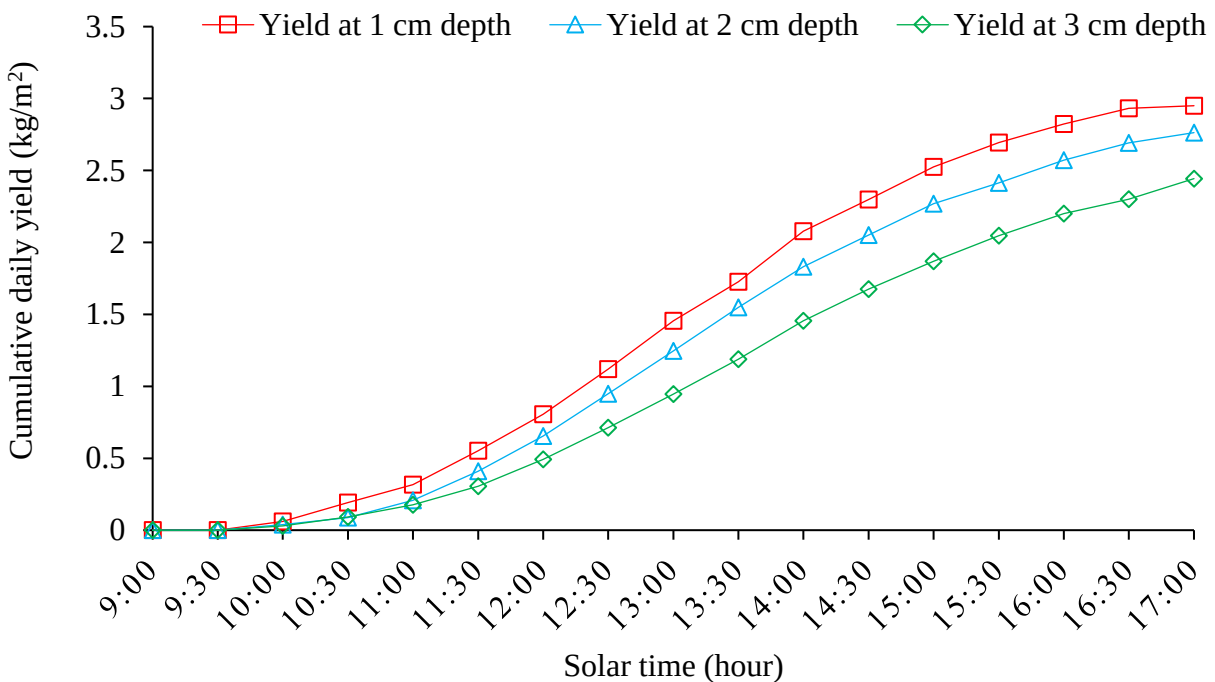


Figure 6.16: Comparison of the cumulative yield for CPSS

From the graph it is observed that the cumulative yield is higher at the depth level of 1 cm and the yield is lesser for the depth level of 3 cm. This is because the evaporation rate of the water in the basin varies with the depth level of the water in the still. Thus, there is an increase of 13% yield for the depth level of 2 cm and 21% increase in the depth level of 1 cm, when compared with the ideal depth level of 3 cm.

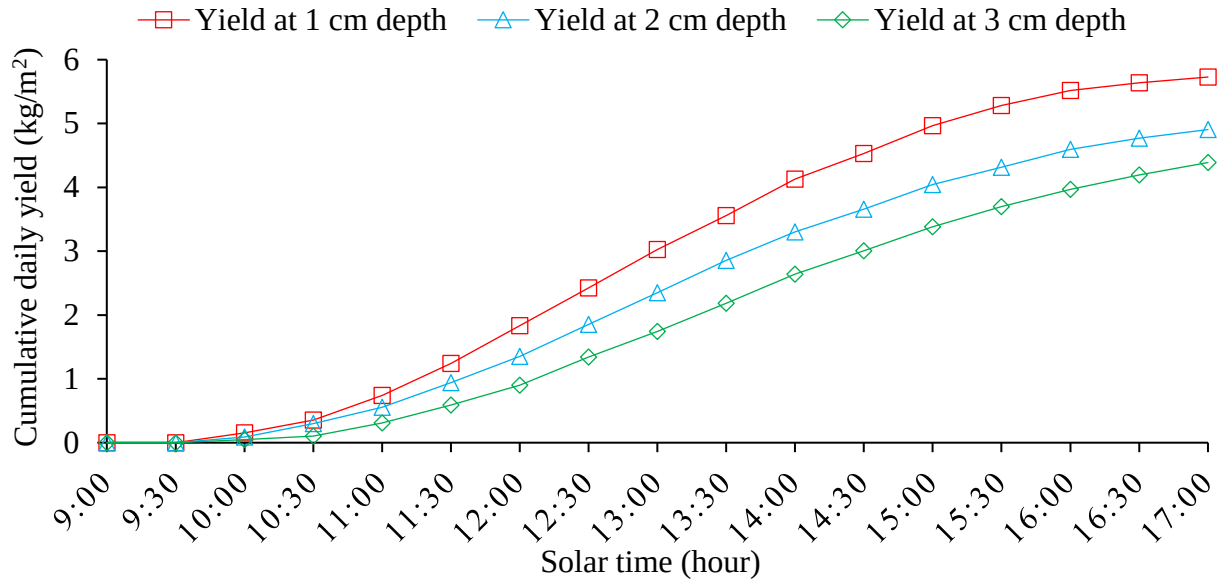


Figure 6.17: Comparison of the cumulative yield for MPSS

For MPSS, the total cumulative yield obtained per m^2 for the water depth of 1, 2 and 3 cm are 5.728, 4.905 and 4.389 L/m^2 day, respectively. Thus, there is increase of 31% yield for the depth level of 1 cm and 12% increase in the depth level of 2 cm, when compared with the ideal depth level of 3 cm, which is similar to the earlier work reported by (Saravanan and Murugan, 2020), for depth of water integrated with various wick materials to improve the yield of solar stills.

The obtained distillate yield is maximum from lower water depth (1 cm) and minimum from higher water depth (3 cm). It can be observed that the amount of distillate yield is inversely proportional to the water depth. This is caused by the higher rate of evaporation (due to higher temperature difference between water and glass) for lower a water depth. Therefore, distillate yield decreases with increase in basin water depth. This proves that the lower basin water depth has a good effect on the distillate output of the still. Also, the amount of yield varies with the depth level in different rate at the high intense and low intense periods. Hence the lower water depth is preferable at the higher intense radiation and the higher depth level is preferable at the lower intense period.

6.3.2 Effects of Proposed Modifications

The effect of proposed modifications with the optimum water depth of 1 cm were examined and recorded in a 30-minute interval. The experimental observations of hourly temperatures with proposed modifications were presented and discussed in the following sub-sections.

6.3.2.1 Experimental Results of Inclusion of V-corrugated Surface

The effect of v-corrugated absorber surface paint with black at optimum water depth of 1 cm were explained in Figure 6.18. Here, the temperature of absorber plate and water were found to be increased from 31 to 67 °C and from 28 to 65 °C with rise in solar irradiation till 12:30 and 13:00 hours, respectively. While, the glass temperature was varied from about 27 to about 53 °C with increase in solar irradiation during 13:00 hours.

The proposed modifications increased the area subjected to water evaporation inside the solar still and maintains higher water temperature in the basin. This ensures more temperature difference between glass and water ($T_w - T_g$) duration the period of entire day. This mostly credited to the effect of significant amount of heat transfer occupied from v-corrugated surface to the water in the basin by means of the capillary action and rise the heat transfer in the air-water interface. An improved solar still yield was observed in a solar still using v-corrugated absorber.

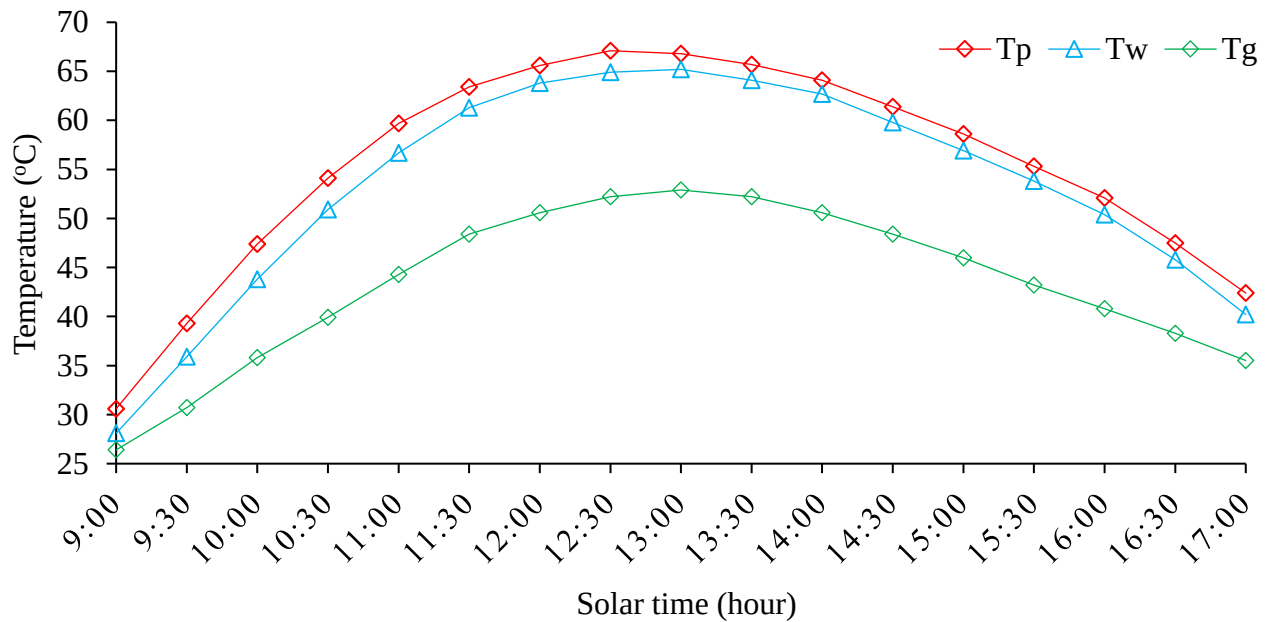


Figure 6.18: Hourly variations of temperatures with v-corrugated absorber surface

6.3.2.2 Effect of Nano-coated Absorber Surface

The impact of nano-coated combined with v-corrugated absorber surface at the concentrations of 3% weight of CuO nanoparticles and optimum water depth of 1 cm were compared in Figure 6.19. The absorber plate temperature was varied from 33 to 74 °C during 13:30 hours. Similarly, temperature of basin water was observed in the range between 30 and 71 °C during 13:30 hours. While, temperature of glass was varied in the range between 29 and 56 °C till 13:30 hours.

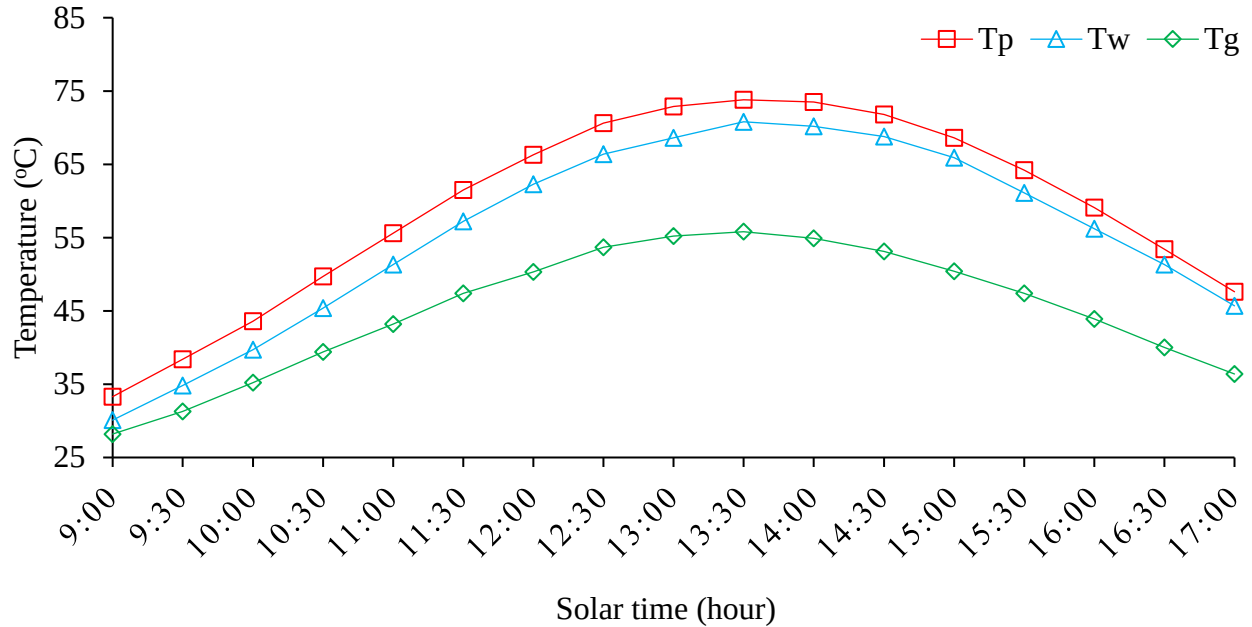


Figure 6.19: Hourly variations of temperatures of with nano-coating surface

It is observed that, the presence of nano-coating has created high temperature differences between the water surface and glazing surface. The CuO nano-coating surface absorbs the heat during forenoon hours and retains to till the end of experimental trials. So, this will enhance the rate of evaporation and improves the yield of freshwater and the thermal performance of solar still.

6.3.2.3 Effect of Internal Reflectors

The impact of internal reflector with CuO nano-coated and v-corrugated absorber surface observed during experiments in solar stills were depicted in Figure 6.20. As expected, it observed that, the maximum temperature of absorber plate increases from about 34 to 79 °C during 13:00 hours. While, the temperature of water was varied in the range of 30 to 76 °C during 13:00 hours, with an average temperature of 53 °C. During morning, the maximum value of glass temperature was varied from about 28 to 62 °C at 13:30 hours and falls down to about 38 °C during 17:00 hours.

It is observed that, the inner surface of solar still with proposed modifications absorbs and retains significant heat due to direct fall of solar radiation. The residual solar radiation has reflected back to water surface and partly absorbed by water vapour and also by the nano-coating. An increase in yield was observed with increase in solar radiation. This is due to increase in heat capacity in the basin and also due to the presence of proposed modifications and reduces heat losses from side.

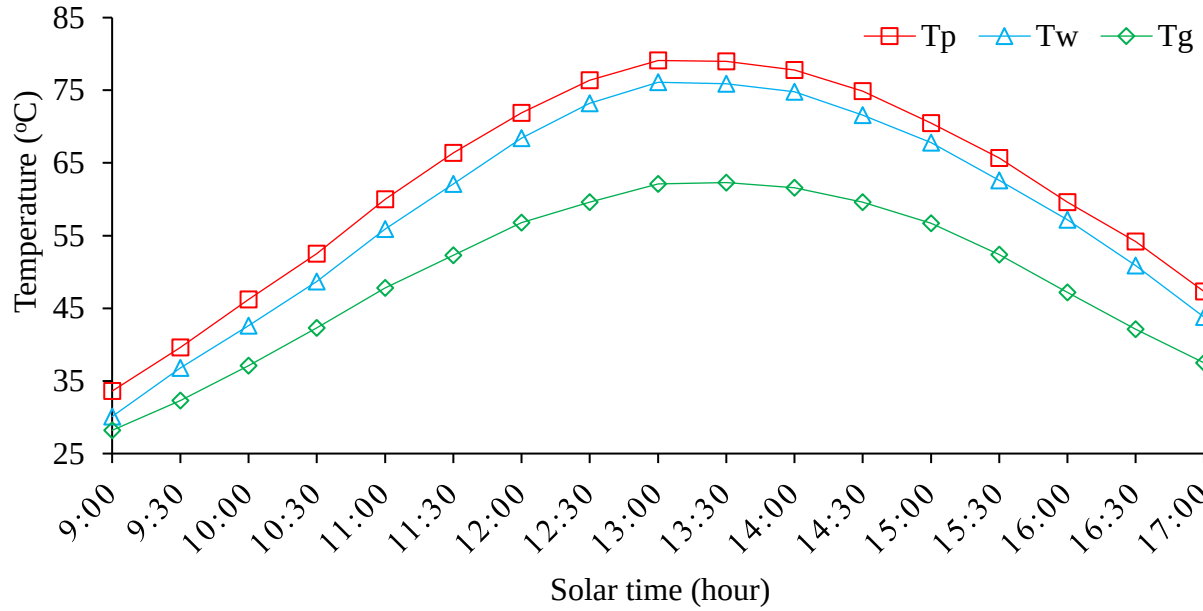


Figure 6.20: Variations of temperatures versus solar time with internal reflectors

6.3.2.4 Effect of Nano-embodied PCM

The influence of nano-PCM with v-corrugated, nano-coated and internal reflectors was examined on the clear day and shown in Figure 6.21. Here, it is observed that, the maximum temperature of absorber plate rises from around 33 to 77 °C during 13:00 hours. The maximum temperature of glass was varied from about 29 to 59 °C at 13:00 hours and falls down to about 34 °C during 17:00 hours. The maximum temperature of water occurred between 31 and 73 °C during 13:00 hours.

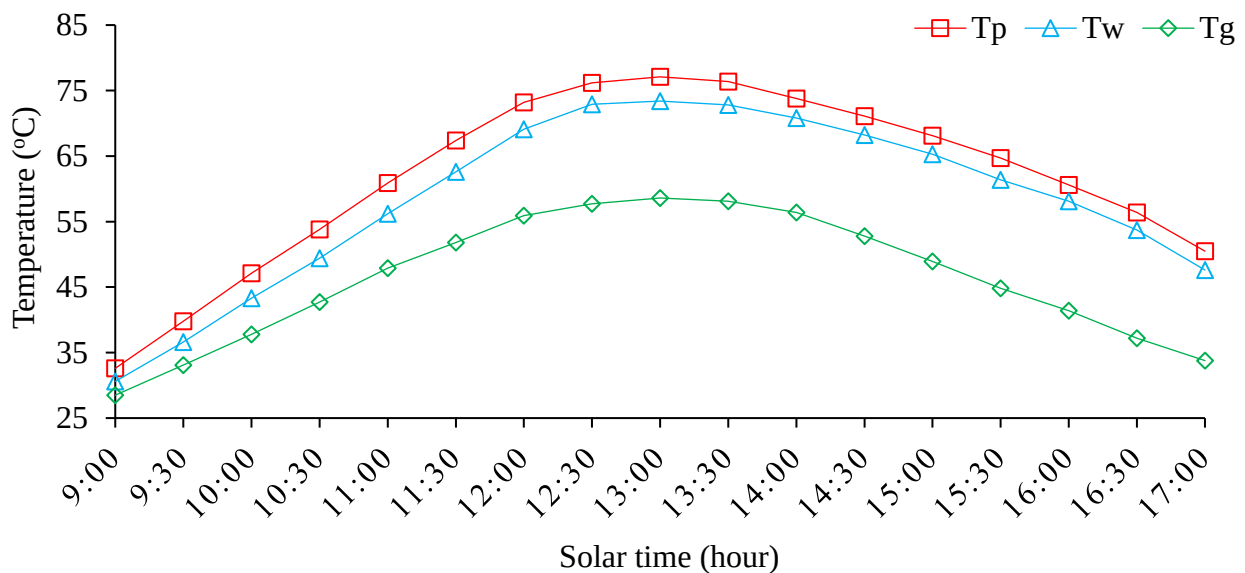


Figure 6.21: Hourly variations of temperatures versus solar time with NPCM

The temperature of PCM increases with time which results in the increase of heat transfer rate from the basin to the PCM. Thermal energy started to store as sensible heat in solid wax till attains its melting point. It is observed that, the presence of NPCM inside the solar still has absorbed the heat during peak sunshine hours and also during condensation of water vapour inside the solar still. The temperature of glass in the presence of proposed modifications was found to be lower when compared to the CPSS. The yield of solar still is influenced by the glass temperature. Hence, it is essential to control the temperature raise of glass in the solar still to attain maximum yield.

6.3.2.5 Cumulative Distillate Yield of Proposed Modifications

The distillate yield of the solar still with proposed modifications at optimum water depth of 1 cm was shown in Figure 6.22. The total cumulative yield obtained per m^2 for the CPSS, v-corrugated, nano-coating with v-corrugated, internal reflectors with nano-coating plus v-corrugated, and nano-enhanced phase change material with nano-coating plus internal reflector plus v-corrugated, during experimental observations are 2.95, 3.37, 4.5, 4.99 and 5.73 L/m^2 day, respectively.

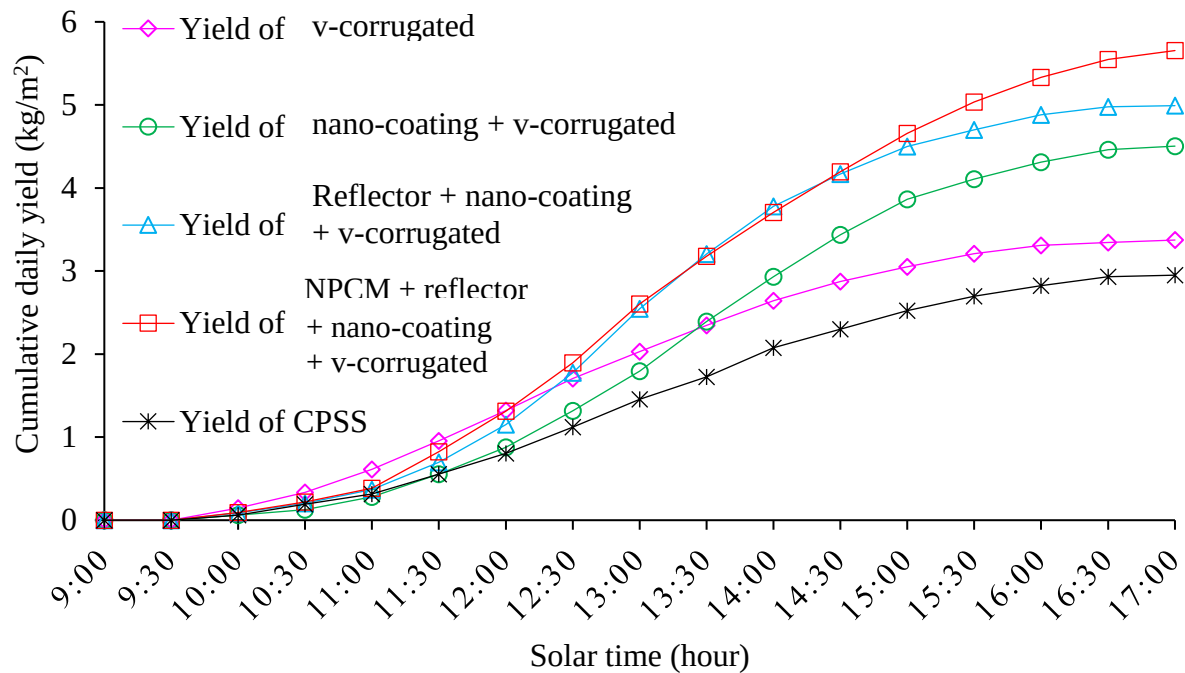


Figure 6.22: Cumulative yield and effects of proposed modifications

Thus, there is an increase of 14% yield for the v-corrugated surface, 53% increase for the nano-coating with v-corrugated, 69% rise for the internal reflector with nano-coating plus v-corrugated, and 94.2% increase for the nano-embodied phase change material with internal reflector plus nano-coating plus v-corrugated, when compared with the conventional pyramid solar still.

6.4 Theoretical Analysis of MPSS under Fantale's Climatic Condition

The solar irradiation is the most influencing parameter affecting the performance of solar stills. Annual solar irradiation potential available at Fantale is more suitable to source the solar still. The theoretical values of maximum basin water temperatures of MPSS were increased from 43 and 80 °C, at around 12:30 hours. While, for 3 cm water depth, the values of maximum basin water temperatures were ranged between 36 and 74 °C, at around 13:30 hours, shown in Figure 6.23.

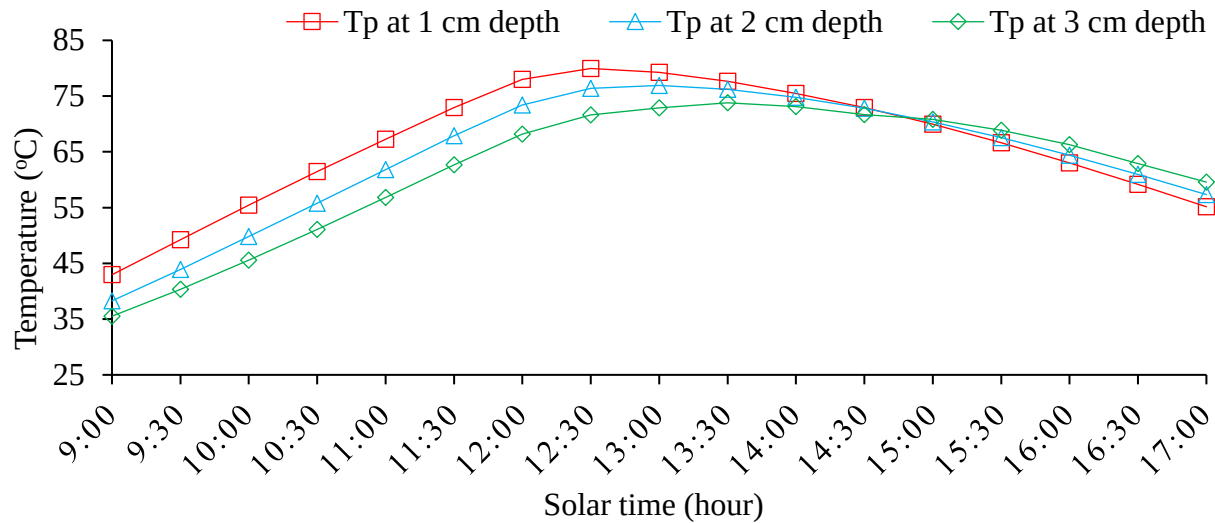


Figure 6.23: Hourly variations of absorber plate temperature with MPSS

It is observed that, for 1 cm water depth the theoretical water temperatures of MPSS in the basin were varied from 41 to 75 °C till 12:30 hours. While, for 3 cm water depth, the values of maximum basin water temperatures were ranged between 33 and 70 °C, at around 13:30 hours, Figure 6.24.

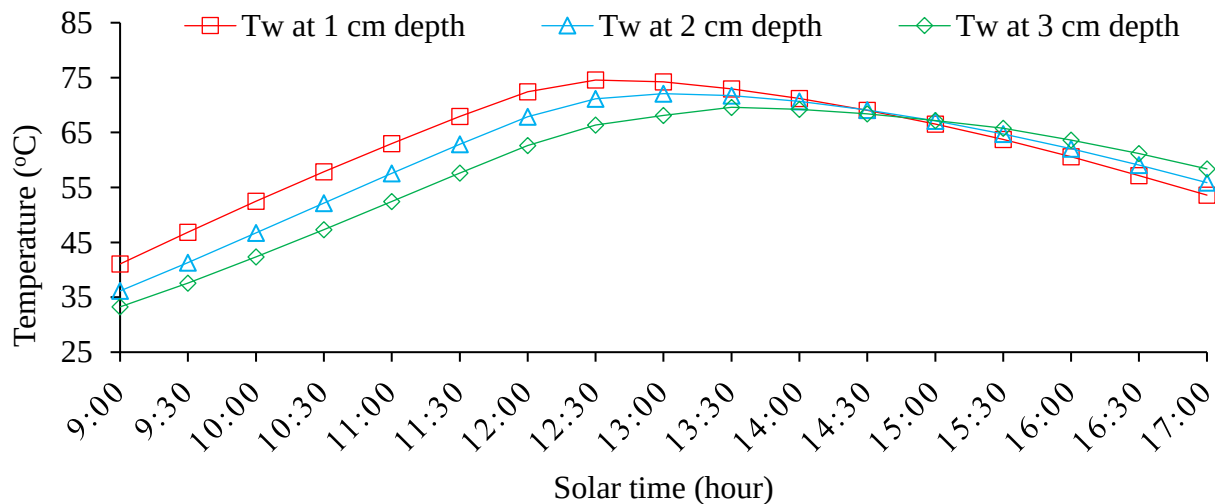


Figure 6.24: Hourly variations of water temperature with MPSS

The theoretical analysis of glass cover temperature of MPSS was amplified from 33 to 64 °C during 12:30 hours at 1 cm water depth, Though, at 3 cm depth of water the theoretical values of the glass temperature was varied in the range between 30 and 57 °C till 13:00 hour, shown in Figure 6.25.

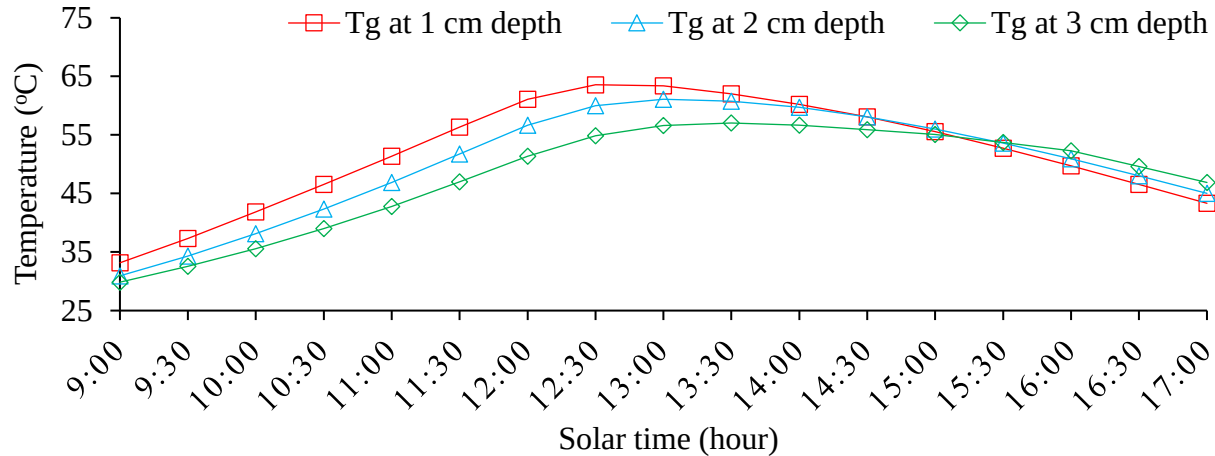


Figure 6.25: Hourly variations of glass temperature with MPSS

During theoretical analysis for MPSS, the total cumulative yield obtained per m^2 at the depth levels of 1, 2 and 3 cm are 6.827, 6.171 and 5.446 L/m^2 day, respectively, shown in Figure 6.26.

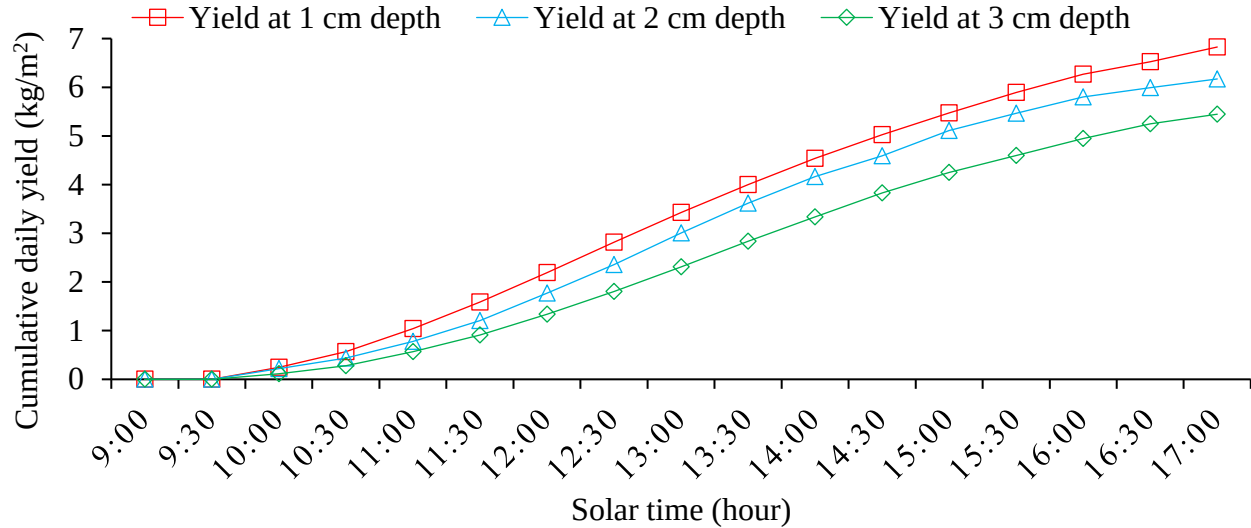


Figure 6.26: Comparison of the cumulative yield for CPSS

From the graph it is observed that the cumulative yield is higher at the depth level of 1 cm and the yield is lesser for the depth level of 3 cm. This is because the evaporation rate of the water in the basin varies with the depth level of the water in the still. Thus, there is an increase of 13% yield for the depth level of 2 cm and 25% increase in the depth level of 1 cm, when compared with the ideal depth level of 3 cm.

6.5 Energy Efficiency

The energy efficiency variations observed in a solar still during experimentation were compared in this section. For the case of CPSS, the experimental daily efficiency revealed was around 43.90, 41.29 and 36.67% at 1, 2 and 3 cm basin water depth, respectively. The energy efficiencies of a MPSS using 1, 2 and 3 cm water depth are found to be about 63.72, 54.53 and 47.65%, respectively. Figure 6.27 illustrates the experimental daily efficiency of CPSS and MPSS, respectively at different water depths.

It is observed that, at 1 cm water depth, the maximum energy efficiency of about 56.03 and 43.9% were observed for MPSS and CPSS, respectively. At 3 cm water depth, the minimum energy efficiency of about 44.17 and 36.67% was observed for MPSS and CPSS, respectively. For both of them the maximum and minimum values of daily efficiency were obtained at 1 and 3 cm basin water depth, respectively. This also proves that the daily efficiency is decreased as the basin water depth is increased. The reason behind this may be that the water temperature is quickly rising for a lower basin water depth due to minimum volume of water and gives the higher amount of yield. Therefore, daily efficiency is greater than that for the higher value of basin water depth.

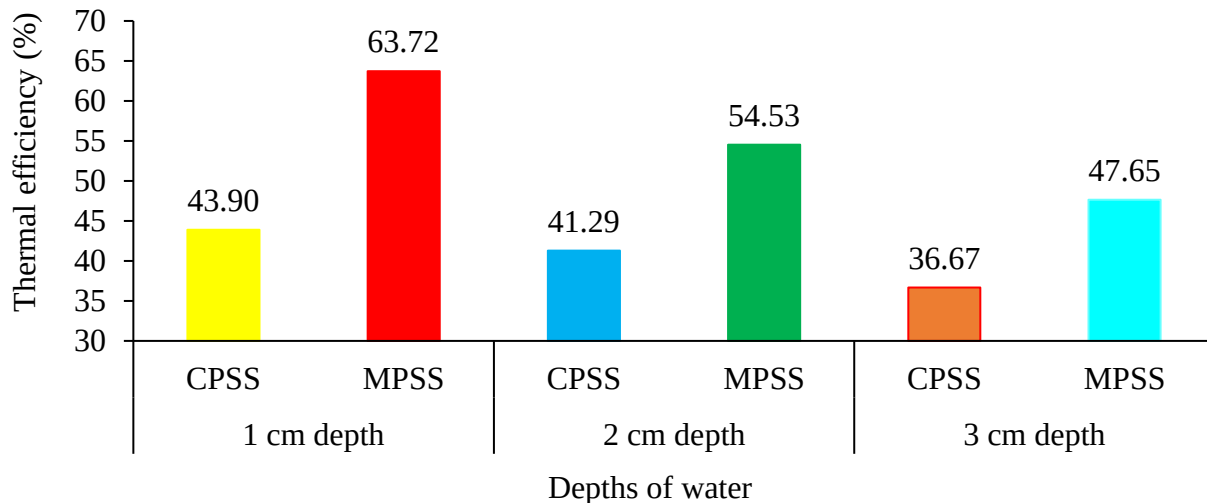


Figure 6.27: Thermal daily efficiency of CPSS and MPSS

The energy efficiency results confirmed that, 1 cm is an optimal water depth, with maximum energy performance. The influence of proposed modifications has improved the energy efficiency of a solar still, which similar to the earlier work reported by (Younes *et al.*, 2022). The energy efficiency variations are similar to the earlier research works reported by (Sharshir *et al.*, 2020).

6.6 Exergy Efficiency

The exergy performance (based on second law of thermodynamics) of a solar still with CPSS and MPSS was estimated to quantify the losses in solar still. The exergy efficiency of CPSS and MPSS observed during experimental values with different depth of water was shown in Figure 6.28.

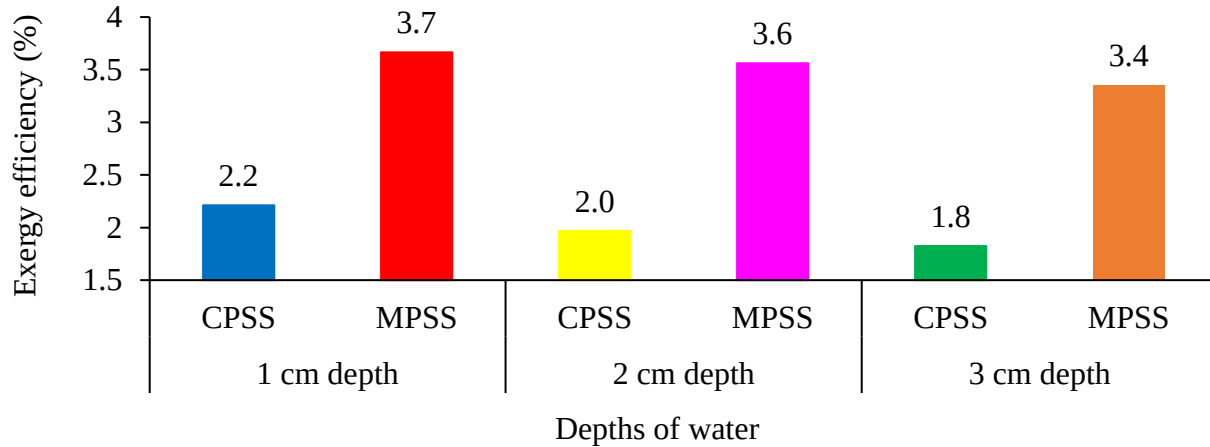


Figure 6.28: Average exergy efficiency of a solar still with CPSS and MPSS

It was observed that, the average exergy efficiencies of a CPSS at 1, 2 and 3 cm water depth were found to be about 2.2, 2.0 and 1.8%, respectively. While, the average exergy efficiencies of a MPSS obtained were about 3.7, 3.6 and 3.4% at 1, 2 and 3 cm water depth, respectively. The maximum exergy variations were observed for in the solar still using 1 cm water depth, which was found to be an optimal water depth to produce maximum yield. The exergy efficiency variations were similar to the earlier research study reported by (Sharshir *et al.*, 2018).

6.7 Comparison of the CPSS and MPSS

Table 6.1 shows the average values of the cumulative yield, daily thermal efficiency, and daily exergy efficiency for both the CPSS and MPSS. The average accumulative distillate water yield during the experimental observations achieved by the MPSS reached 5.73 L/m²/day compared to 2.95 L/m²/day was achieved by a reference still (CPSS), representing 94.2% average enhancement in accumulative yield. The average daily thermal efficiency during the experimental observations of CPSS reached 43.90%, while the adding the incorporated effective four modifications on design MPSS enhanced the average thermal daily efficiency to 63.72% with improvement 45.1%. Also, the average daily exergy efficiency during the experimental observations of CPSS reached 2.2%, while the adding the incorporated effective four modifications on design MPSS enhanced the average daily exergy efficiency to 3.7% with 68.2% improvement in daily exergy efficiency.

Table 6.1: Average values of yield, thermal and exergy efficiency of CPSS and MPSS

S. No	Case study	CPSS	MPSS
1.	Average cumulative yield	2.95 L/m ² /day	5.73 L/m ² /day
2.	Improvement in distillate yield	-	94.2%
3.	Average daily thermal efficiency	43.90%	63.72%
4.	Improvement in daily thermal efficiency	-	45.1%
5.	Average daily exergy efficiency	2.2%	3.7%
6.	Improvement in daily exergy efficiency	-	68.2%

Based on the above results, the utilization of the effective four hybrid modifications is the good idea to achieve the highest performance of modified solar distiller. The proposed modifications in the present study are in agreement with earlier research work reported by (Abdullah *et al.*, 2020).

6.8 Comparison of Present Study with Previous Research Work

A comparison between yield values obtained by other researchers and those obtained in the present work was shown in Table 6.2.

Table 6.2: Comparison of the present work with earlier research works

Authors	Classification	Analysis	Efficiency (%)	Yield (L/m ² day)	Modifications
Gupta <i>et al.</i> , (2017)	Single slope SS	Experimental	54.5%	4.0	Sprinkler attachment and nanoparticles
Sharshir <i>et al.</i> , (2020)	Pyramid solar still	Experimental	60.5	5.0	v-corrugated, wick materials, nanocoating
Present research work	Pyramid solar still	Experimental	63.72	5.73	v-corrugated, CuO nano-coated, NPCM and internal reflectors

Kianifar *et al.*, (2012) performed experimental analysis on pyramid solar still to show the effect small fan and water depth at Mashhad, Iran. They reported that the daily yield with small fan (active solar still) at water depths of 4 and 8 cm was 3.14 and 3.05 L/m²/day, respectively in the summer season. While, without small fan (passive solar still), they found that the yield was 2.72 and 2.56 L/m²/day at water depths of 4 and 8 cm, respectively. The experimental yield value of

conventional pyramid solar still of present work at a water depth of 2 and 3 cm for conventional pyramid solar still was very close to the above values without small fan.

6.9 Water Quality Analysis

The water samples of saline water were taken from the Lake Basaka around Fantale Woreda. In this present study, the physical and chemical tests were performed for both saline and distilled water. The distilled water from the solar stills was collected in glass bottle. Tests were conducted at the department of Chemistry laboratory, ASTU. The physio-chemical analysis of saline and distilled water was tested on 19-22/05/2022. The permissible results obtained and accessible limits set by WHO was also noted. Table 6.3 depicts the quality parameters of saline and distilled water. The detailed photography of tested water and devices used were depicted in Appendix F.

Table 6.3: Water quality analysis of saline and distilled water

S. No	Name of test	Actual test result found		Standard requirements
		Saline water	Distilled water	
1.	pH value	9.73	6.76	6.5–8.5
2.	Electrical conductivity (EC) (mS)	3.17	0.391	0.5 mS
3.	Total dissolved solids (TDS) (ppt)	2.06	0.254	0.5 ppt
4.	Fluoride (F) (mg/L)	0.294	0.02	0.05 mg/L
5.	Turbidity (NTU)	6.79	4.48	5 NTU
6.	Total hardness (mg/L)	35	21	25 mg/L
7.	Calcium hardness (mg/L)	8	4	5 mg/L
8.	Magnesium hardness (mg/L)	4	3	4 mg/L
9.	Nitrate (NO ₃) (mg/L)	1.1	<0.05	0.05 mg/L
10.	Odour	Agreeable	Agreeable	Agreeable
11.	Colour	Colourless	Colourless	Agreeable
12.	Taste	Saline	None	Agreeable

From the obtained results it was clear that the solar still reduces most of the impurities well below the standards set by WHO. The water quality test has been done for saline and distilled water, shows good agreement with WHO limit and the obtained purified water is suitable for drinking purposes and other applications. The water quality test done in the present study are in agreement with earlier research work reported by (Jobrane *et al.*, 2022; Shanmugan *et al.*, 2020).

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The present thesis investigated the experimental performance of modified passive solar still using nanoparticles for desalinating saline water. The components of the solar still was designed based on the daily requirements of drinking water for an average rural family and constructed from locally available materials. The analyzes were carried out with two distinct pyramid solar still: one is a modified pyramid solar still and the other is a conventional pyramid solar still that serves as the reference case. Experimentation and theoretical analysis were conducted in four phases. In the first phase, experiment and theoretical analysis were conducted to examine conventional solar still without any modifications. In the second phase, the effects of several modifications such as v-corrugated basin, nano-coating absorber plate, nano-enhanced PCM and internal reflector on the performance of conventional solar still were studied experimentally. In the third phase, the impact of various concentrations of nanoparticles on the yield of freshwater were conducted. In the fourth phase, comparison and analysis of the best operating parameters for the maximum yield of freshwater with the conventional and modified solar still were carried out. Analysis of the energy and exergy efficiency were performed to assess the performance of the solar still components and overall system. Data were recorded from the experimentation which include measurement of temperature and yield of freshwater. Experimental results and verification of the theoretical analysis was showed a good agreement. Lastly, water quality test and cost analysis of the solar still was conducted. The following conclusions were drawn from the experimental and theoretical analysis of the solar still:

- The average yield of freshwater found from CPSS was obtained as 2.95 L/m² day and from the MPSS was 5.73 L/m² day efficient, with improvement of 94.2%.
- The use of v-corrugated surface improves the yield (3.37 L) by 14%, use of nano-coating with v-corrugated augments the yield (4.5 L) by 53%, use of internal reflector with nano-coating plus v-corrugated enhances the yield (4.99 L) by 69%, and use of nano-PCM with internal reflector plus nano-coating plus v-corrugated boosts the yield (5.73 L) by 94.2%, when compared with the yield (2.95 L) of CPSS.
- Addition of PCM in the solar still reduces the rate of heat loss and supplied energy at noon.

- Blend of nanoparticles to the black paint increases the thermal conductivity, which acts as absorbing material and enhances the yield.
- The average thermal efficiency of the CPSS and MPSS were 43.9 and 63.72%, respectively, with enhancement of 45.1%. The average exergy efficiency of the CPSS and MPSS were 2.2 and 3.7%, respectively, with improvement of 68.2%.
- The water quality test has been done for saline and distilled water, shows good agreement with WHO limit and the obtained freshwater is suitable for drinking.

7.2 Recommendations

In the present study, theoretical and experimental investigation on the performance of passive solar still using nanoparticles and suitable design modifications for desalinating saline water has been carried out. The key results of the research have been underlined in section 7.1. However, there are lots of scopes for further research to improve the system performance. Some of the future scopes and recommendations for further studies are as follows:

- In this study, passive solar still was investigated for desalination process. Thus, future work should focus on active solar still such as integrating with photovoltaic source.
- Since solar radiation is not available throughout the whole year, integrating other renewable energy mechanisms like biomass to support the solar still system can be studied.
- Further improvements like addition of wick basin, sensible heat energy storage and etc. can enhance its performance and thereby enhancing the yield.
- In this study, the small scale solar still was designed for an average rural family. Thus, the still can be investigated further for large scale application.
- The theoretical and experimental results of present work can be analyzed and future work should focus on simulation using computational fluid dynamics.

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APPENDIXES

Appendix-A: X-ray Diffractometer (XRD) Result

The XRD test was conducted at the department of Material Science and Engineering, ASTU. The instrument used was Shimadzu diffractometer XRD-700 model, with scattering angle (2θ) between 10° to 80° . The XRD pattern of CuO nanoparticle shows that the high and sharp intensity of 2θ phase was obtained and shown in Figure A-1.

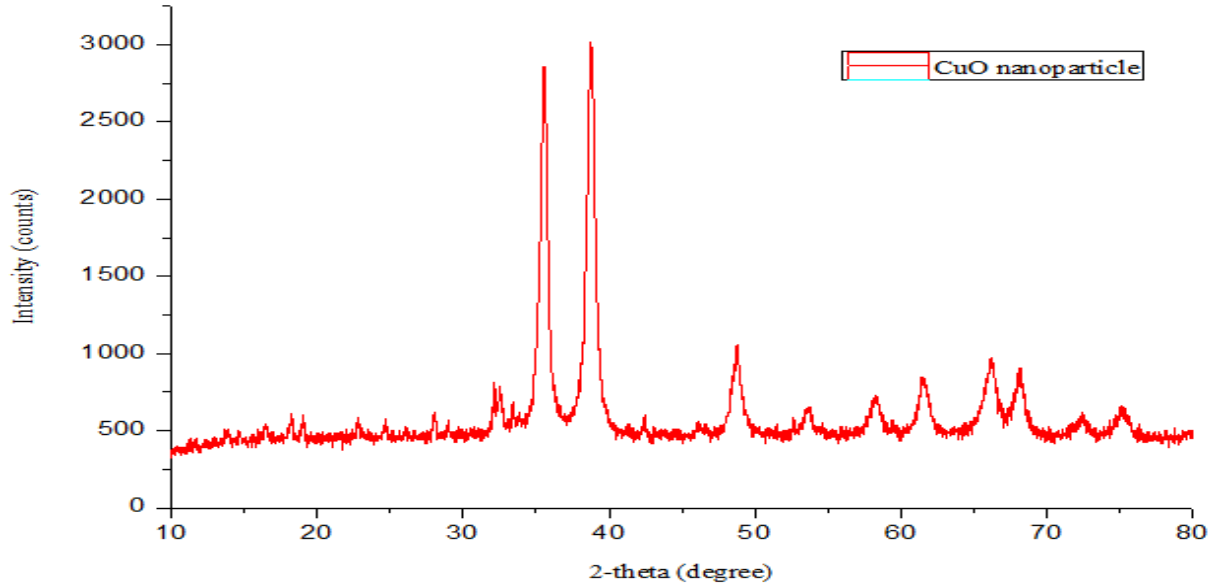


Figure A-1: XRD pattern of CuO nanoparticle

All the peaks in diffraction pattern shows monoclinic structure of CuO, and the peaks. XRD results confirmed that the CuO nanoparticle were crystalline. The diffraction peaks can be indexed to those of pure face-centered cubic corresponding to the peak planes, in good agreement with literature. The y-axis shows the numbers of nanoparticle exist at each peak with respective diffraction angle and x-axis indicates the diffraction peaks with respective nanoparticle. The diffraction peaks of nanoparticle were significant to estimate the average particle size. This XRD result is almost similar with that of (Suresh and Kalaiselvam, 2017; Ahamed *et al.*, 2014) in which the particles sizes found to be 12-14 nm as stated in literature.

Appendix-B: Analytical Analysis of Nanofluid

For the MPSS, the effect of varying concentrations of nanoparticles was applied to improve solar radiation absorption and thermal conductivity while lowering specific heat. Varying concentration of nanoparticles by 1, 2 and 3% weight with base fluid were executed with theoretical analysis. To

provide a valid comparison at different concentrations of CuO nanoparticle, a constant amount of base fluid was maintained. The effect of various concentrations of nanoparticles were explained in this sub sections.

Estimation of Nanoparticle Volume Concentration

The various concentration of CuO nanoparticles were added to the constant amount of volume of base fluid. Basically, this addition of nanoparticle improved the properties of nanofluid compared to base fluid. For the entire experimental process, the optimum concentration of the nanoparticles was maintained and the corresponding readings were recorded. The properties of nanofluid obtained from the theoretical analysis were depicted in Figure B-2.

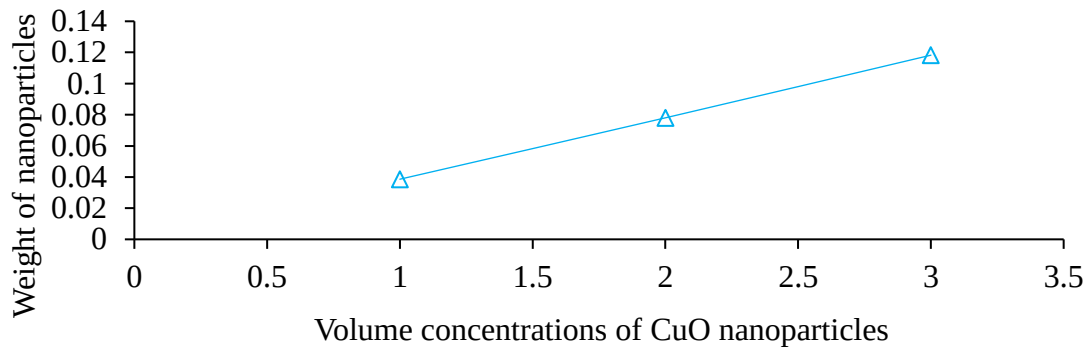


Figure B-2: Relation of volume concentration and weight of nanoparticle

It is observed that, the addition of various concentrations of copper oxide nanoparticle to the base fluid was increased sharply with weight of nanoparticles. Addition of nanoparticle to the constant amount of volume of base fluid increases the concentration of nanoparticle in the nanofluid.

Thermal Conductivity of Nanofluid

In order to increase the thermal conductivity of the base fluid nano sized particles was added to it. Consequently, increasing the concentration of nanoparticle to the base fluid rapidly increases the thermal conductivity of nanofluid, was shown in Figure B-3. This due to the increasing of the size of cluster of nanoparticles in the base fluid which results high conductivity occur in this large cluster of nanoparticles. When the concentration of nanoparticle added to the base fluid was increased, different types of clusters formed and this formation of different shape of nanoparticle cluster increase the thermal conductivity of nanofluid.

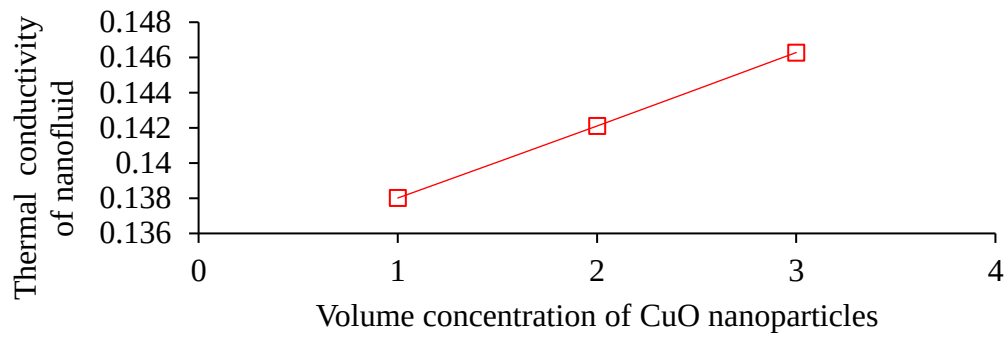


Figure B-3: Relation of volume concentration and thermal conductivity of nanofluid

It is observed that, initially the thermal conductivity of nanofluid linearly increases because of the thermal properties of nanofluid such as specific heat capacity, density and clustering of fluid vary with change of concentration.

Specific Heat Capacity and Density of Nanofluid

The specific heat capacity of nanofluid decreased with the increased concentration of the nanoparticle in the base fluid, was shown in Figure B-4. This is due to the increasing of thermal conductivity of nanofluid as a result of repaid heat transfer occurs in the nanofluid.

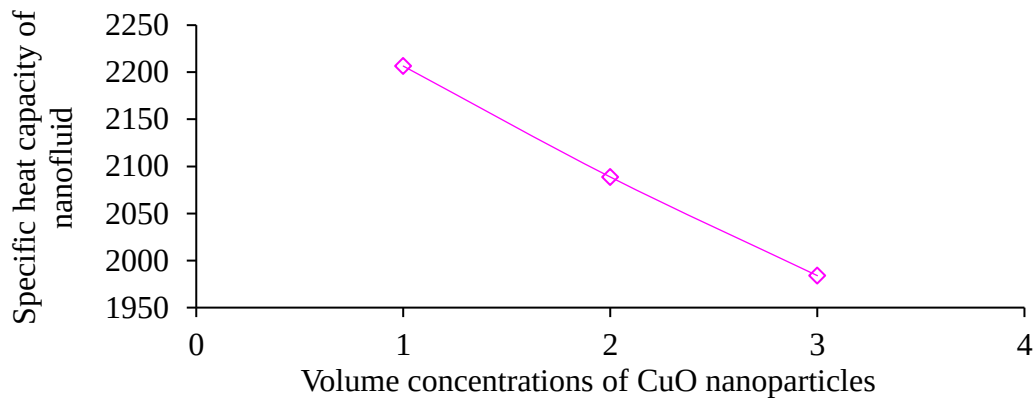


Figure B-4: Volume concentration of nanoparticles versus specific heat capacity

The addition of nanoparticle to the base fluid increases the density of nano fluid. The density of nanofluid increased as result of the increasing concentrations of nanoparticle in the base fluid, was revealed in Figure B-5.

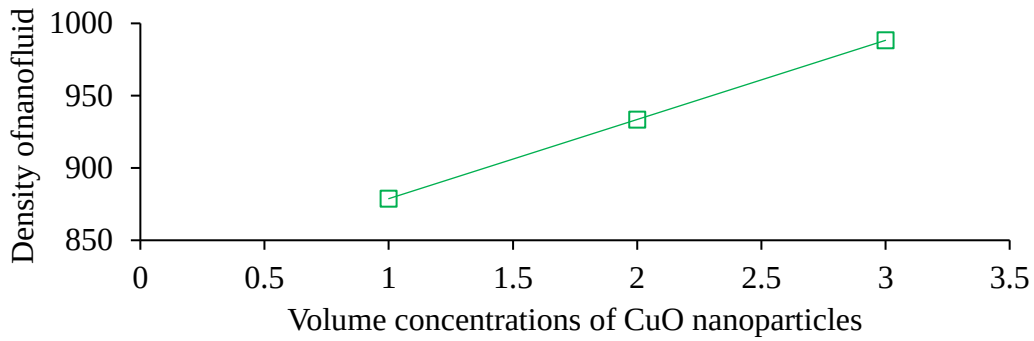


Figure B-5: Volume concentration of nanoparticles versus density

Since the density of the nanoparticle was greater than the base fluid. As a result, the density of nanofluid increases linearly and the specific heat capacity of nanofluid decreases sharply.

Estimation of Viscosity of Nanofluid

The viscosity of fluid is the resistance of fluidity of a liquid. The viscosity of nanofluid increased while increased the concentration of nanoparticle in the base fluid. This is due the addition of nanoparticle made high resistance between particles of nanofluid compared to base fluid. The viscosity of nanofluid increased linearly while increasing concentration of nanoparticle to base fluid because of the nanoparticle decreasing the flowing properties of base fluid.

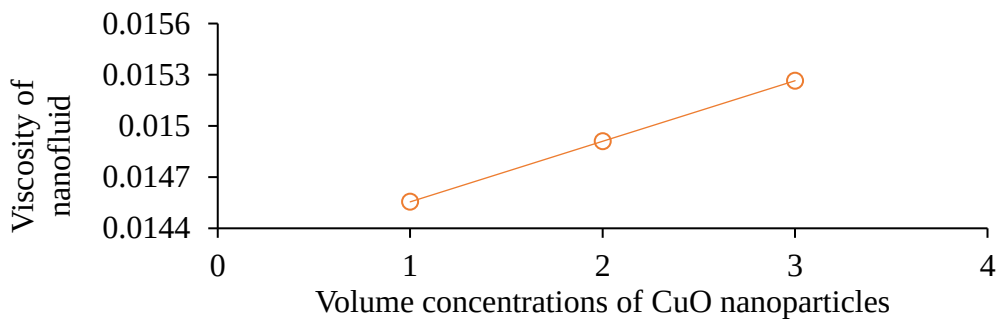


Figure B-6: Relation of volume concentration and viscosity of nanofluid

It is observed that, the addition of nanoparticle to base fluid increases the concentration of nanoparticles, thermal conductivity, density and viscosity of nanofluid, whereas decreases the specific heat capacity of nanofluid, which augment the evaporative, radiative, and convective heat transfer coefficients. Therefore, for the entire experimental procedure, 3% weight concentration of nanoparticles was optimum and maintained for the intention of experimentation.

Appendix-C: Experimental Observation with Various Depth of Water

Table C-1: Experimental observation of the CPSS at 1 cm water level

Time (hour)	I (W/m ²)	T _a (°C)	T _p (°C)	T _w (°C)	T _{gi} (°C)	m _w (kg/m ²)	M _w (kg/m ²)
9:00	475.345	25.3	31.3	28.6	28.4	0.000	0.000
9:30	555.76	26.5	38.9	34.1	32.1	0.000	0.000
10:00	627.041	28.1	45.2	39.8	35.3	0.061	0.061
10:30	686.09	27.6	50.8	45.6	38.7	0.131	0.191
11:00	730.285	29.8	55.3	50.9	41.5	0.125	0.316
11:30	757.634	27.7	59.1	55.0	43.8	0.237	0.553
12:00	766.891	31.8	62.3	58.1	45.9	0.253	0.806
12:30	757.634	32.9	63.8	60.2	47.1	0.313	1.120
13:00	730.285	32.1	63.4	61.1	47.3	0.335	1.455
13:30	686.09	34.2	62.6	60.9	47.0	0.272	1.727
14:00	627.041	33.5	61.2	60.3	46.5	0.351	2.078
14:30	555.76	33.8	59.3	58.8	45.4	0.221	2.299
15:00	475.345	31.4	56.6	55.8	43.3	0.226	2.525
15:30	389.183	29.9	53.1	52.1	40.1	0.170	2.695
16:00	300.764	31.6	48.8	48.8	36.8	0.128	2.823
16:30	213.477	29.1	44.7	44.7	34.2	0.108	2.932
17:00	130.426	28.4	40.5	40.4	28.6	0.018	2.950

Table C-2: Experimental observation of the CPSS at 2 cm water level

Time (hour)	I (W/m ²)	T _a (°C)	T _p (°C)	T _w (°C)	T _{gi} (°C)	m _w (kg/m ²)	M _w (kg/m ²)
9:00	473.957	25.6	29.8	27.4	26.8	0.000	0.000
9:30	554.166	26.2	34.9	31.6	29.6	0.000	0.000
10:00	625.263	27.6	40.5	36.3	32.7	0.038	0.038
10:30	684.159	28.4	46.4	41.5	35.9	0.050	0.089
11:00	728.24	29.4	52.2	46.6	38.7	0.118	0.207
11:30	755.519	30.1	56.3	51.4	41.1	0.204	0.411
12:00	764.752	31.8	58.9	55.7	43.1	0.244	0.655
12:30	755.519	32.4	60.8	58.2	44.5	0.294	0.949
13:00	728.24	33.8	61.7	59.1	45.2	0.296	1.245
13:30	684.159	34.5	61.1	59.5	45.5	0.303	1.548
14:00	625.263	33.7	60.2	59.1	45.3	0.283	1.831
14:30	554.166	32.4	58.8	57.7	44.5	0.221	2.052
15:00	473.957	31.6	56.4	55.4	42.9	0.217	2.269
15:30	388.017	30.2	53.2	52.6	40.8	0.145	2.414

16:00	299.825	29.7	50.1	49.7	38.1	0.157	2.571
16:30	212.762	28.8	47.4	46.8	35.4	0.121	2.692
17:00	129.924	27.4	43.5	43.5	33.2	0.071	2.763

These two tables are noted for a sample, other data also there, but it takes more number of pages.

Appendix-D: Thermocouple Calibration

Calibration of thermocouples is essential to confirm the correct temperature and can be calibrated with a standard thermocouple in thermal laboratory. Calibration test for four-channel K-type digital thermocouple was conducted with standard thermocouple by using 1.5 kg of water boiling and cooling test for 29 minutes.

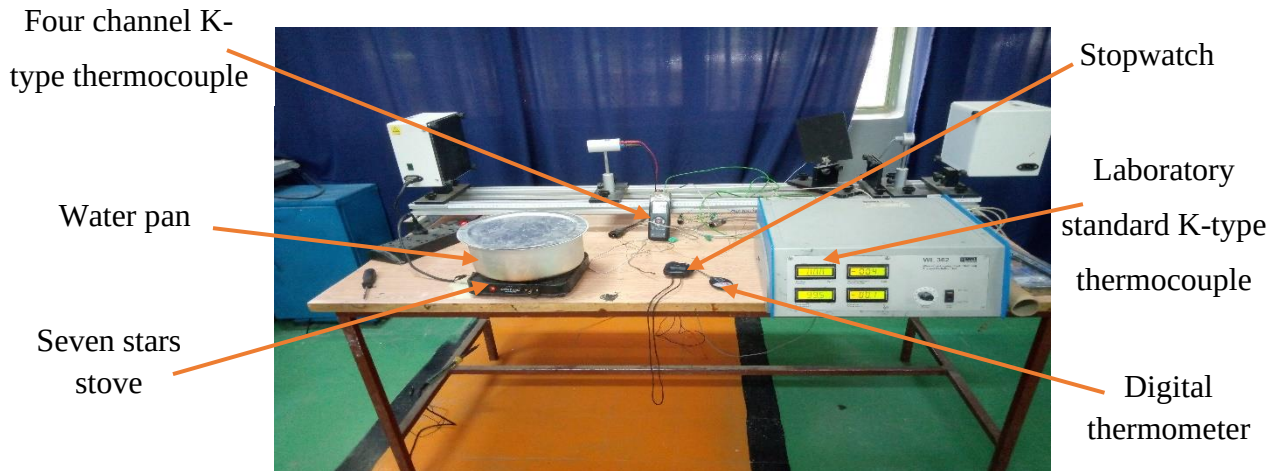


Figure D-7: Calibration setup with standard and K-type thermocouples

Data recorded with the help of standard thermocouple and K-type thermocouple during calibration was depicted in Table D-3.

Table D-3: Water temperature measuring test by using K-type thermocouples

Time (minute)	T _{w1} (Standard thermocouple)	T _{w2} (four channel K-type Thermocouple)	Uncertainty (%) [(T _{w1} -T _{w2})/ T _{w1}] × 100
1	93.4	93.2	0.21413
3	90.8	90.6	0.22026
5	87.3	86.9	0.45819
7	83.2	82.9	0.36058
9	80.8	80.5	0.37129
11	76.7	76.4	0.39113
13	72.7	72.3	0.55021

15	68.1	67.7	0.58737
17	62.6	62.4	0.31949
19	59.8	59.4	0.66890
21	50.5	50.2	0.59406
23	41.8	41.4	0.95694
25	37.4	37.1	0.80214
27	30.8	30.6	0.64935
29	25.5	25.3	0.78431

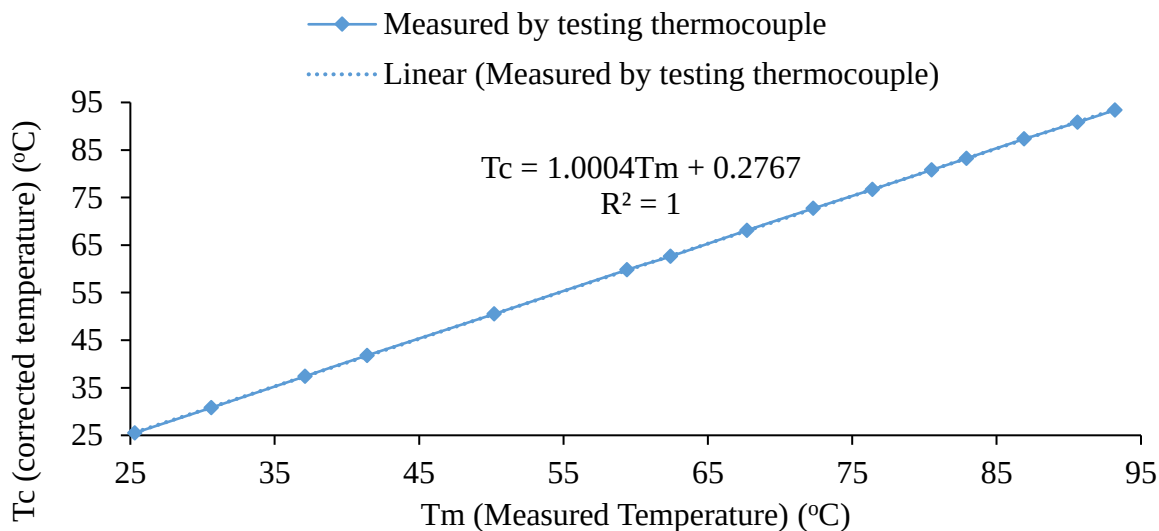


Figure D-8: Measured Temperature versus Corrected temperature

Appendix-E: Description of Measuring Instruments used and their Accuracy

Thermocouple: The temperatures of the absorber plate, glass, and saline water were recorded with the help of K-type thermocouples. The accuracy of the thermocouples is $\pm 0.1^{\circ}\text{C}$. The minimum experimental value measured is 25°C . The error occurred in the temperature measurement is the ratio between the least count and minimum value of the temperature measured. Therefore, the maximum possible error is $0.1/25 = 0.004$. Percentage error (% error) = $0.004 \times 100 = 0.4\%$.

Digital thermometer: The temperature of the ambient was measured with help of digital thermometer. The range of measuring temperature is -50°C to $+200^{\circ}\text{C}$ with the accuracy of $\pm 0.1^{\circ}\text{C}$. Least experimental value is 25°C . The obtained resolution is $0.1/25 = 0.004$. % error = 0.4% .

Distilled collection: For measuring distilled water, borosilicate glass was used. The capacity of the beaker was 1 liter. The accuracy of the borosilicate glass is $\pm 1\text{ mL}$. The minimum value of measured distilled water is 100 mL. Maximum possible error = $1/100 = 0.01$, % error = 1%

Table E-4: Accuracy and error for various measuring instruments

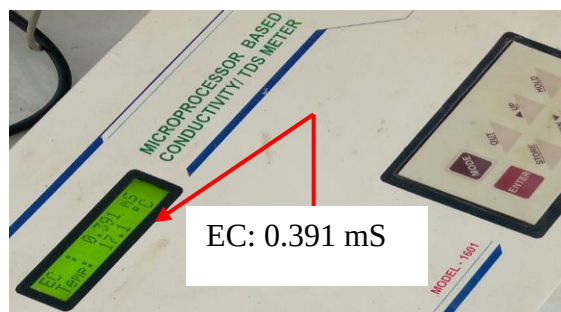
Instrument	Model	Range	Accuracy	Error
Thermocouple	K-type thermocouple	0 - 100 °C	± 0.1 °C	0.4%
Thermo meter	Digital thermometer	0 - 100 °C	± 0.1 °C	0.4%
Distilled collection	Borosilicate glass	± 5 mL	0 - 1000 mL	1%

Appendix-F: Figures Taken during Water Quality Test

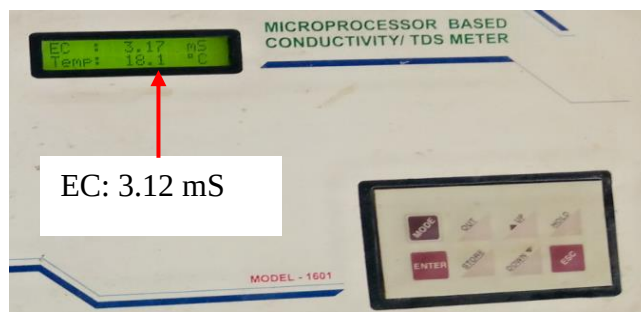
Methods and instruments used to find the physical and chemical properties of water samples.

Table F-5: Methods and instruments used to find the physio-chemical properties of water

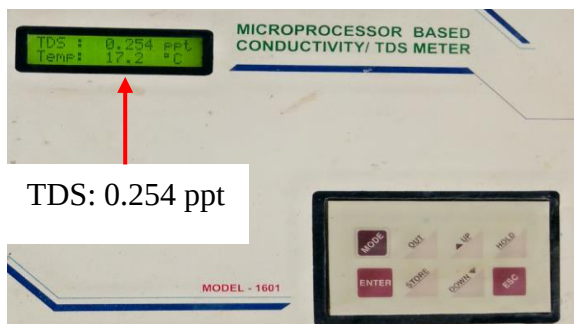
S. No	Name of test	Methods or Instruments used
1.	pH value	Microprocessor pH meter
2.	Electrical conductivity (mS)	Microprocessor based conductivity
3.	Total dissolved solids (ppt)	Microprocessor TDS meter
4.	Turbidity (NTU)	Turbidity meter (Turbidimeter)
5.	Fluoride (F) (mg/L)	PF Fluoride tester and titration
6.	Total hardness (mg/L)	By summation of magnesium and calcium hardness
7.	Calcium hardness (mg/L)	Titration with an EDTA solution
8.	Magnesium hardness (mg/L)	Titration with an EDTA solution
9.	Nitrate (NO ₃) (mg/L)	Photo Lab S6
10.	Odour	Qualitatively measurement
11.	Colour	Visual comparison method
12.	Taste	Taste comparison method



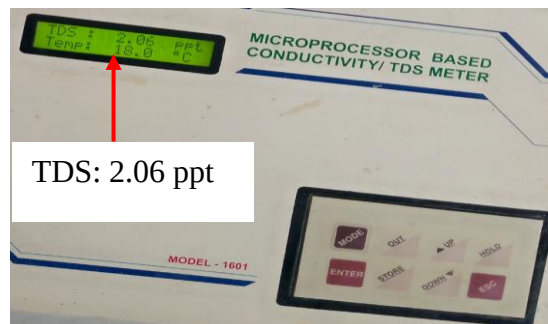
Microprocessor EC meter (a) For distilled water



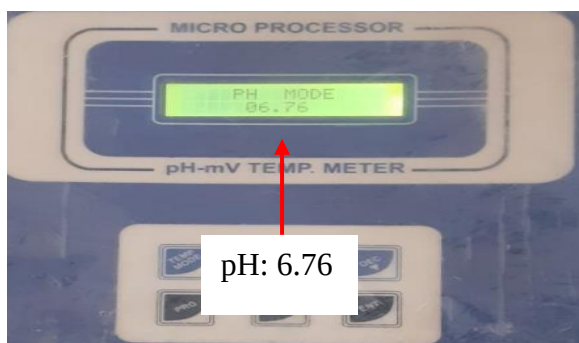
(b) For saline water



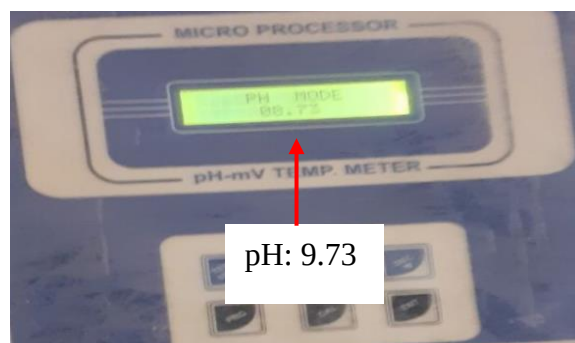
Microprocessor TDS meter (c) For distilled water



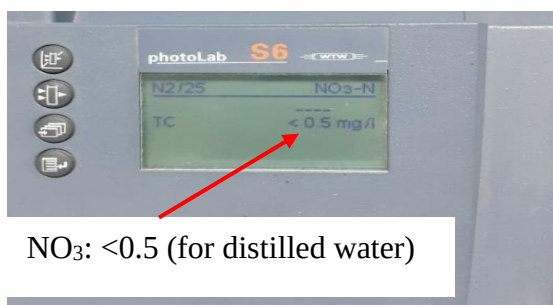
(d) For saline water



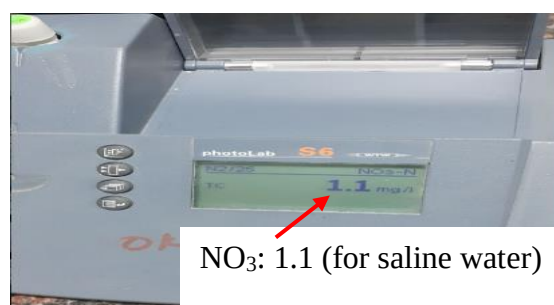
Microprocessor pH meter (e) For distilled water



(f) For saline water



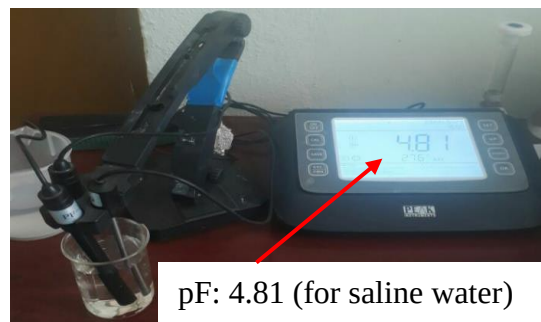
NO₃: <0.5 (for distilled water)



NO₃: 1.1 (for saline water)



pF: 5.82 (for distilled water)



pF: 4.81 (for saline water)

For distilled water: $[F] = 10^{-Px} \times 1000 \times 19 \Rightarrow [F] = 10^{-5.82} \times 1000 \times 19 = 0.02 \text{ mg} / \text{L} = 0.02 \text{ ppm}$

For saline water: $[F] = 10^{-Px} \times 1000 \times 19 \Rightarrow [F] = 10^{-4.81} \times 1000 \times 19 = 0.294 \text{ mg} / \text{L} = 0.294 \text{ ppm}$

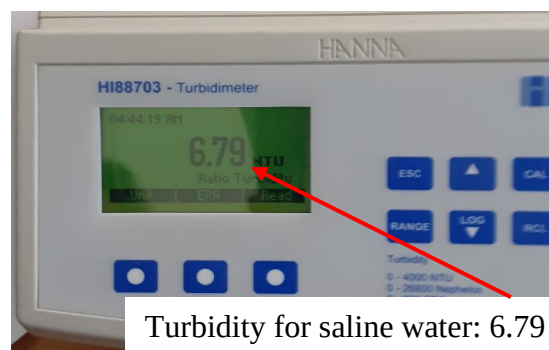
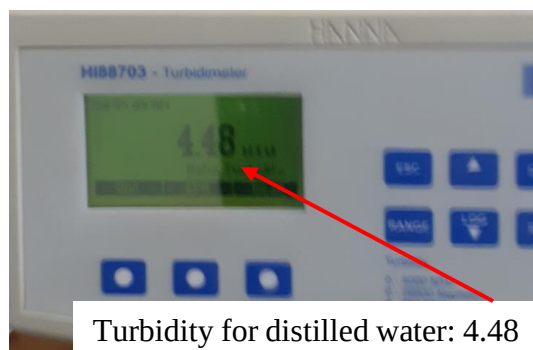


Figure F-9: Figures taken during water quality analysis

Appendix-G: Economic Analysis

The cost per liter of water production and benefit cost ratio was evaluated to optimize the construction costs and economic analysis of the solar desalination (Shoeibi *et al.*, 2021). Economic evaluation of any system is the most necessary part of today's time. The usage of solar energy seems to provide a great future as we can use such type of energy source all time. However, the basic problem arises is the initial cost of the system that we are using like the development of the solar still. Therefore, it becomes necessary to analyze such system economically.

Initial Investment

Let us suppose P is the initial investment cost of the solar still which includes the cost of structure, labor cost, cost of glass cover, paint cost and all other such of costs. Suppose i denotes the annual rate of interest of a bank loan (12% in this study) and n denotes the lifetime years of the solar still which is assumed to be ten (10) years. The detailed initial investment cost of the conventional and modified pyramid solar still was presented in Table G-6.

Table G-6: Equipment and initial investment cost of the proposed solar still

S. No	Description cost		Quantity	Unit price	Amount (ETB)	
	Material	Specification			CSS	MSS
1.	Wooden box and insulation	1 m × 2 m	1	500.00	500.00	500.00
2.	Galvanized iron sheet	1 m × 2 m	1	900.00	900.00	900.00
3.	Glass cover	1 m × 2 m	2	700.00	1,400.00	1,400.00
4.	Water outlet and inlet	1/2" Diameter	3	50.00	150.00	150.00
5.	Paint, sealing etc.	1 gallon	1	170.00	170.00	170.00
6.	Nanoparticles	1 gallon	1	500.00	-	500.00

7.	PCM	1 packet	1	2,050.00	-	2,050.00
8.	Labour and miscellaneous	Days	2	100	200	200.00
Total				3,320.00	5,870.00	

Cost of Water Production

The main target of any solar still system is to cut down the cost of production per liter (CPL) of distillate water. The studied cases of CPSS and MPSS are economically examined and the most significant factors which are used for the economic analysis of solar still and its procedures can be summarized as follows:

(a) First Annual Cost (FAC): The FAC of a solar still is given by (Yousef *et al.*, 2019):

$$FAC = CRF \times P \dots\dots\dots (G.1)$$

where P and CRF represent the capital cost and the capital recovery factor of the SS, respectively.

(b) Capital Recovery Factor (CRF): The CRF is a technique for cost analysis, which determines the success of the investment and is computed by the ratio of a fixed annuity to the amount of achieving that annuity for a specific period of time (Shoeibi *et al.*, 2021) and as follows:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \dots\dots\dots (G.2)$$

Where: i - the rate of interest per year on the capital amount and n - number of useful life in years up to which the system will perform

(c) Annual Salvage Value (ASV): The ASV is defined as the value of the components of a solar still in its lifetime (Mevada *et al.*, 2021). The ASV of the solar still is given by:

$$ASV = (SFF) \times S \dots\dots\dots (G.3)$$

where SSF and S denotes the sinking fund factor (SFF) and the salvage value of the solar still.

(d) Salvage Value (S): The salvage value of solar desalination is equal to twenty percentage (20%) of the used all components cost of solar desalination. S is given by (Essa *et al.*, 2021): Salvage value of a system is equal to 20% of Capital cost (P) i.e.

$$S = 0.2 \times P \dots\dots\dots (G.4)$$

(e) Sinking Fund Factor (SFF): SSF is given by (Vikram *et al.*, 2021):

$$SFF = \frac{i}{(1+i)^n - 1} \dots\dots\dots (G.5)$$

(f) Annual Maintenance Cost (AMC): The AMC includes the annual price of repair and utilization of the solar desalination, which is considered to account for 15% of the primary price. The AMC per year is supposed 15% of the first annual cost (Kianifar *et al.*, 2012):

$$AMC = 0.15 \times (FAC) \dots\dots\dots (G.6)$$

(g) Annual Cost (AC): The whole AC of the solar still is given by (Yousef *et al.*, 2019):

$$AC = FAC + AMC - ASV \dots\dots\dots (G.7)$$

Where: CF (cost of freshwater) = yearly yield x selling price of fresh water (CPL)

(h) Cost per Liter (CPL): The CPL is defined as the ratio of the whole AC to the annual freshwater yield (P_n) of solar still. The CPL of the freshwater yield is estimated by:

$$CPL = \frac{AC}{P_n} \dots\dots\dots (G.8)$$

Where AC is the annual cost and P_n represents the average annual freshwater yield per square meter of water production. It should be noted that the average yearly production of distilled water for the considered solar still systems is estimated as the average value of the production of distilled water for the test day, multiplied by the number of clear days in the year. Assuming that, the solar still system is working about 300 day/year. The annual yield produced from CPSS and MPSS is 2.95 and 5.73 L/m² day, respectively.

This the price of water is obtained by

$$PoW = P_n \times CoW \dots\dots\dots (G.9)$$

in which CoW presents the cost of water and is equal to 15 ETB per liter in Ethiopia. The cost analysis and annual distilled water yield of the proposed systems was tabulated in Table G-7.

Table G-7: Economic analysis of the conventional and modified pyramid solar stills

S. No	Type	CPSS	MPSS
1.	Lifetime years of the solar still (n) (year)	10	10
2.	Annual rate of interest of a bank loan (i) (%)	0.12	0.12
3.	Capital Recovery Factor (CRF)	0.177	0.177
4.	Initial investment cost of the solar still (P) (ETB)	3,320	5,870

5.	Salvage Value (S)	664	1,174
6.	First Annual Cost (FAC)	587.6	1,038.9
7.	Sinking Fund Factor (SFF)	0.057	0.057
8.	Annual Salvage Value (ASV)	37.84	66.89
9.	Annual Maintenance Cost (AMC)	88.14	155.84
10.	Annual Cost (AC)	637.89	1,127.832
11.	Average yearly distillate production (P_n)	885	1,719
12.	Cost per Liter (CPL)	0.721	0.656
13.	Price of water per liter (PoW) (ETB/L)	10.8	9.75

An economic analysis was conducted to know the economic feasibility of the stills. As observed, the price of water yield per liter for the MPSS was lower than that of the CPSS. From the economic analysis, it is clear that the price of water per liter produced from MPSS is inexpensive 9.75 ETB/L/m², as compared to the CPSS is 10.8 ETB/L/m².

Appendix-H: MATLAB Program Code

%% This code is developed to solve the radiation data analysis for each day and months of the year,
 %%that feed to the next codes on the solar still analysis. The row data for the sunshine, temperature
 %%and windspeed is taken from the National Metrology Agency, Adama branch of Ethiopia.

mon = ['Jan', 'Feb', 'Mar', 'Apr', 'May', 'Jun', 'Jul', 'Aug', 'Sep', 'Oct', 'Nov', 'Dec']; %Month of year

n = [17 47 75 105 135 162 198 228 258 288 318 344]; %representative day of each month

ns = [9.25 9.52 9.02 8.24 8.70 8.14 7.06 6.96 7.37 8.60 8.84 9.21]; %sun shine hours

lat = 8.983; % Latitude of Fantale village

Isc = 1367; % Solar constant

ST=1:24; % Solar time hour

y=1:12; % Number of months in year

for i=1:length(ST)

 for j=1:length(y)

 dec (j) = 23.45*sin((360*(284+n(j))/365)*pi/180); %declination angle

 ws (j) = acos(-tand(lat)*tand((dec (j))))*180/pi; %sunset hour angle

 wsr (j) = 12 - (1/15)* acos(-tand(lat)*tand((dec (j))))*180/pi;...

 ... %sunrise hour angle

 wss (j) = 12 + (1/15)* acos(-tand(lat)*tand((dec (j))))*180/pi; ...

```

... %sunset hour angle
Ns (j) = 2*ws(j)/15; %number of daylight hours
%%a1, b1, a2 and b2 are regression parameters
a1 (j) = -0.110 + 0.235*cosd(lat)+ 0.323*ns(j)/Ns(j);
b1 (j) = 1.449 - 0.533*cosd(lat) - 0.694*ns(j)/Ns(j);
a2 (j) = 0.409 + 0.5016*sin((ws(j) - 60)*pi/180);
b2 (j) = 0.6609 - 0.4767*sin((ws(j) - 60)*pi/180);
Iext (j) = Isc*(1 + 0.033*cos((360*n(j)/365)*pi/180));%solar rad exit
w(i)=(ST(i)-12)*15; %Solar time
Ho (j) = (24*3600/pi)*Iext(j)*(cosd (lat) * cosd (dec(j))* sind ...
...(ws(j))+(pi/180)*ws(j)*sind (lat)* sind (dec(j)))/10^6; %Daily
extraterrestrial radiation on a horizontal surface
H (j) = Ho(j)*(a1(j)+ b1(j)*ns(j)/Ns(j)); %Monthly average daily ...
... global solar radiation
Hd (j) = H(j)*(0.931 - 0.814*ns(j)/Ns(j)); %Monthly average daily ...
... diffuse radiation
Hb (j) = H(j) - Hd(j); %Monthly average daily beam radiation
I(i,j) =(pi()/24)*H(j)*(a2(j)+b2(j)*cos(w(i)*pi/180))* ...
...(cos(w(i)*pi/180) - cos(ws(j)*pi/180))/(sin(ws(j)*pi/180)-...
...(pi/180)*ws(j)*(cos(ws(j)*pi/180))); %Monthly average hourly
...global radiation(MJ/m^2)
I(I<0)=0;
Id(i,j)=(pi()/24)*Hd(j)*(cos(w(i)*pi/180)-cos(ws(j)*pi/180))/ ...
...(sin(ws(j)*pi/180)-(pi/180)*ws(j)*(cos(ws(j)*pi/180)));
...%Monthly average hourly diffuse radiation on a horizontal
Id(Id<0)=0;
Ib(i,j) = I(i,j) - Id(i,j); %Monthly average beam radiation on a ...
z(j)=24-Ns(j);
%%%Estimation of Total Incident Solar Radiation on a Tilted Surface
ref = 0.2; %reflectivity (0.2 for bare earth and 0.7 for snow)
beta = 30; %The tilt of a collector on a horizontal surface
ZA(i,j)=(cosd(lat)*cosd(dec(j))*cosd(w(i)))+(sind(dec(j))*sind(lat));
...%Zenith angle of the sun every hour and day of the year

```

```

IA(i,j)=(((cosd(lat)*cosd(beta))+(sind(lat)*sind(beta)))* ...
... (cosd(dec(j))*cosd(w(i)))+(sind(dec(j))*((sind(lat)*cosd(beta))
-(sind(beta)*cosd(lat))));
IA(IA<0)=0;%Incidence angle of the sun every hour and day of the year
Rb(i,j)=IA(i,j)/ZA(i,j); %Beam radiation factor
Rd=(1+cosd(beta))/2; %Diffuse radiation factor
Rr=(1-cosd(beta))/2; %Reflectivity radiation factor
It (i,j)= Ib(i,j)*Rb(i,j)+Id(i,j)*Rd+(Ib(i,j)+Id(i,j))*ref*Rr; %Total
...hourly solar radiation on a tilted surface

end
end
figure(1); %Daily extraterrestrial radiation on a horizontal surface
plot(y,H,'+-r', y,Hd,'-s', y,Hb,'<-b', 'LineWidth', 1);
legend('Global (H)', 'Diffuse (Hd)', 'Beam (Hb)')
xlabel('Month')
ylabel('Solar radiation (MJ/m^2/day)')
title('Solar radiation vs Month')
figure (2); %Monthly average hourly global radiation on a horizontal surface
plot(y,I,'LineWidth', 1);
legend('Jan', 'Feb', 'Mar', 'Apr', 'May', 'Jun', 'Jul', 'Aug', 'Sep', 'Oct', 'Nov', 'Dec')
xlabel('Month')
ylabel('Hourly global radiation (MJ/m^2/day)')
title('Solar radiation vs Month')
figure (3); %Monthly average hourly diffuse radiation on a horizontal surface
plot(y,Id,'LineWidth', 1);
legend('Jan', 'Feb', 'Mar', 'Apr', 'May', 'Jun', 'Jul', 'Aug', 'Sep', 'Oct', 'Nov', 'Dec')
xlabel('Month')
ylabel('Hourly diffuse radiation (MJ/m^2/day)')
title('Solar radiation vs Month')
figure (4); %Monthly average beam radiation on a horizontal surface
plot(y,Ib,'LineWidth', 1);
legend('Jan', 'Feb', 'Mar', 'Apr', 'May', 'Jun', 'Jul', 'Aug', 'Sep', 'Oct', 'Nov', 'Dec')
xlabel('Month')

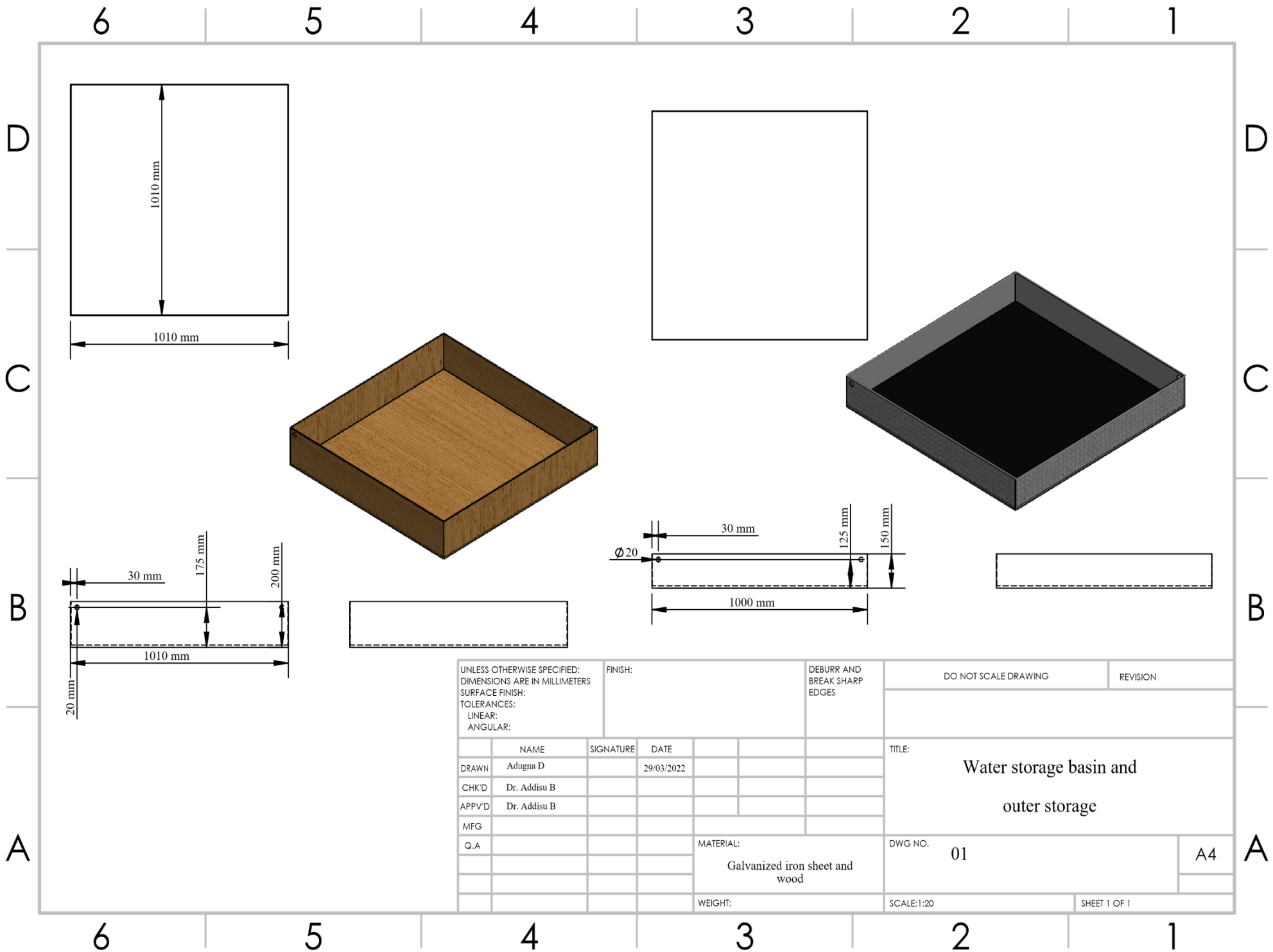
```

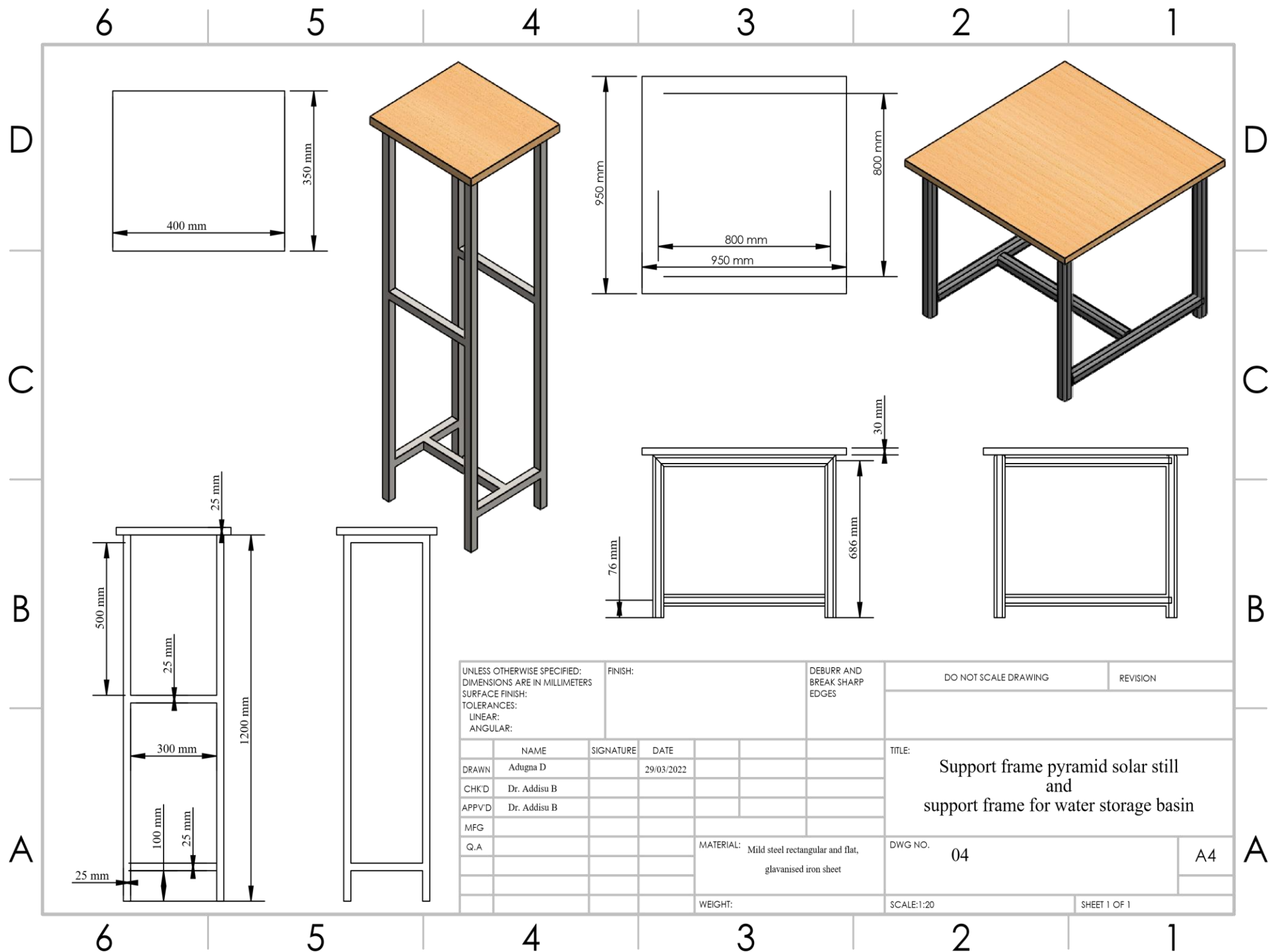
```

ylabel('Hourly global radiation (MJ/m^2/day)')
title('Solar radiation vs Month')
%%% Estimation of Hourly Variation of Ambient Temperature
m=input('enter the month number of the year e.g. Jan=1 Feb=2...Dec=12: ');
mon = ['Jan', 'Feb', 'Mar', 'Apr', 'May', 'Jun', 'Jul', 'Aug', 'Sep', 'Oct', 'Nov', 'Dec']; %Month of year
Tmax = [31.99 33.79 36.45 36.34 36.54 37.15 33.69 32.99 33.87 33.11 32.98 ...
...31.6]; %Maximum temperature of the day of Fantale area
Tmin = [12.81 15.8 18.63 20.27 19.84 21.77 20.6 20.33 19.7 17.08 15.42 ...
...12.71]; %Minimum temperature of the day Fantale area
a=1.8; %Lag coefficient for Tmax
b=2.2; %Night time temperature coefficient
Ns= [11.5 11.7 11.9 12.2 12.4 12.5 12.4 12.3 12.0 11.8 11.6 11.4]; %Day Length
z=24-Ns; %Night length time
wsr = [6.2 6.1 6.0 5.9 5.8 5.7 5.8 5.9 6.0 6.1 6.2 6.2]; %Sunrise hour
wss=[17.8 17.9 18.1 18.1 18.2 18.3 18.2 18.1 18.0 17.9 17.8 17.7]; %Sunset hr
for i=1:length(ST)
    if i<wss(m)&i>wsr(m)
        T(i)=(Tmax(m)-Tmin(m))*sin(pi*(ST(i)-wsr(m))/(Ns(m)+2*a))+Tmin(m);
        ... % calculate daytime temperature
    elseif i<wsr(m)
        T(i)=((Tmax(m)-Tmin(m))*sin(pi*(wss(m)-wsr(m))/(Ns(m)+2*a))+Tmin(m)-...
        ...Tmin(m))*exp(-b*(6+ST(i))/z(m))+Tmin(m); % temperature up to 6 am
    else
        T(i)=((Tmax(m)-Tmin(m))*sin(pi*(wss(m)-wsr(m))/(Ns(m)+2*a))+Tmin(m)-
        ...Tmin(m))*exp(-b*(ST(i)-wss(m))/z(m))+Tmin(m); %Temperature of sunrise
    end
end
figure (5); %Hourly temperature variation analysis
plot (ST,T,'-ob','linewidth',1)
xlabel ('solar time (hr.)')
ylabel ('Temperature (°C)')
title ('Ambient temperature ')

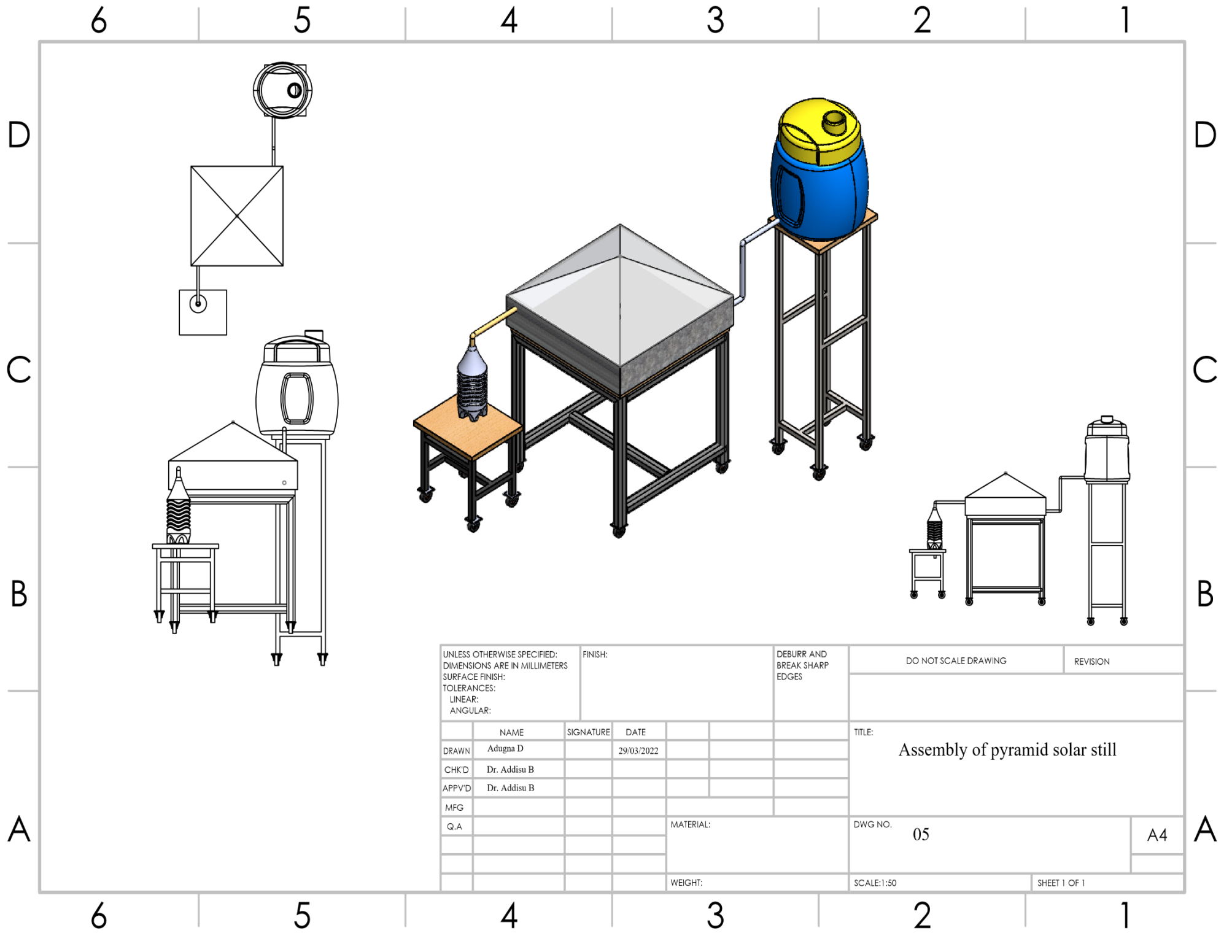
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Appendix-I: Drawing of Solar Still Parts





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:				FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION			
	NAME		SIGNATURE		DATE				TITLE: Support frame pyramid solar still and support frame for water storage basin				
DRAWN	Adugna D				29/03/2022								
CHK'D	Dr. Addisu B												
APPV'D	Dr. Addisu B												
MFG													
Q.A						MATERIAL: Mild steel rectangular and flat, galvanised iron sheet		DWG NO. 04				A4	
						WEIGHT:		SCALE:1:20				SHEET 1 OF 1	



SPECIAL ACKNOWLEDGEMENT

This research project is funded by Adama Science and Technology University under the grant number ASTU/SM-R/654/22, Adama, Ethiopia.