Performance Analysis of Solar Thermal Powered Chicken Egg Incubator with Thermal Energy Storage

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Presented in Partial Fulfillment of the Requirements

of the Degree of

Master of Science in Thermal Engineering

Office of Graduate Studies

Adama Science and Technology University

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DECLARATION

I hereby declare that this M.Sc. thesis entitled "**Performance Analysis of Solar Thermal Powered Chicken Egg Incubator with Thermal Energy Storage"** is my original work. That is presented in partial fulfillment of the requirements for the award degree of Master of Sciences in Thermal Engineering is an authentic record of my work under the supervision of Dr. Addisu Bekele, Associate Professor of Thermal Engineering, Adama Science and Technology University.

The matter embedded in this thesis has not been submitted for the award of a degree or diploma in any other university. All relevant resource information used in this paper has been duly acknowledged.

Belina Amsalu Yadeta	________________	________________
Candidate	Signature	Date

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief. This thesis has been submitted for examination with my approval.

Dr. Addisu Bekele	________________	________________
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RECOMMENDATION

I the advisor of this thesis, hereby certify that I have read the thesis entitled "**Performance Analysis of Solar Thermal Powered Chicken Egg Incubator with Thermal Energy Storage**" prepared under my guidance by **Belina Amsalu Yadeta** submitted in partial fulfillment of the requirements for the degree of Masters of Science in Thermal Engineering.

Therefore, I recommend the submission of the thesis to the department following the applicable procedures.

Dr. Addisu Bekele	______________________	_______________
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APPROVAL SHEET

I hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the dissertation entitled "**Performance Analysis of Solar Thermal Powered Chicken Egg Incubator with Thermal Energy Storage"** by Belina Amsalu Yadeta.

Dr. Addisu Bekele ____________________ ______________________

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We, the undersigned, members of the board of examiners of the final open defense by **Belina Amsalu** have read and evaluated his thesis entitled **"Performance Analysis of Solar Thermal Powered Chicken Egg Incubator with Thermal Energy Storage"** and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfillment of the requirements of the degree of Master of Science in Thermal Engineering.

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ACKNOWLEDGEMENT

First and foremost I would like to thanks my Almighty God for his uncountable blessing given to me. Without his mercy and favors nothings is possible. “Thank You my Lord Jesus!”
I would like to thanks my supervisor, Dr. Addisu Bekele (Associate Professor of Thermal Engineering, Adama Science and Technology University), who made the work possible. His guidance and advice have been extremely useful throughout all stages of the work.
I would also wish to express my gratitude to Dr. Gezhagn Habtamu for giving me valuable suggestions during my proposal presentation which have contributed greatly to the improvement of the thesis. Also, I would like to extend my warmest gratitude to my teachers who have taught me the MSc course works.
My special thanks are extended to, my family for their continuous support and understanding. Above all, thanks to my father Amsalu Yadeta, and my mother Megerse Ayana for their support and prayers during my study period.
This thesis has been written during my study period at the Thermal and Aerospace Engineering Department of Adama Science and Technology University. I would like to thanks all the staff members of Thermal and Aerospace engineering and my entire classmate.

Belina Amsalu Yadeta

August 2021

Adama, Ethiopia

PROVERB

"You Have Your Own Radiance but The Traditions and Conventions of Man Have Told You That You Have No Light!" Dr. MYLES MUNROE

ABSTRACTS

Poultry production is one the most important in household income and food security of the farmers in Ethiopia. It is mainly from traditional producers which are based on a broody hen. Researches show that Poultry production is one of the economic sources of our community. The production is performed traditionally by natural incubations and electric-powered incubators. In this work, a detailed experimental study has been conducted to evaluate the performance of the solar thermal chicken egg incubator with thermal energy storage for hatching chicken eggs.

The work aims to study the performance of solar thermal chicken egg incubators with thermal energy storage under Adama weather conditions. Temperature and humidity are the most important physical factors that affect the system's operation (eggs incubation and embryonic development). In this study, solar thermal energy is used as the energy source of the system. Solar radiation is abundant in the city. It is estimated as average global radiation of 29.7MJ/m^2/day which gives an average of 6.63 kWh/m^2 /day with an average relative humidity of 54.6%. The flat plate collector with an expanded mesh is used for converting solar radiation into thermal energy. The values of hourly hot air temperature leaving the solar collector are collected for March 31, April 04, and April 08, 2021. The temperature starts increasing morning from 8 PM and then decreasing to 6 AM. The average hourly temperature is measured as 52 ℃. *The maximum air temperature obtained is at 2 PM i.e.*75℃. *The collector has an average efficiency of 37.10%. The total required heat for the system and keeping it at the incubation temperature per day is estimated as 4MJ. For solving the intermittence behavior of the solar radiation the thermal energy storage unit is used. The LHS is selected and designed to store the required thermal energy for the system. The 15 kg of paraffin wax enclosed in a rectangular container has been used as latent heat energy storage of the system. It was designed for storing the thermal energy for the system, but only 61.10% (percent) of energy required by the system is recovered by the system. The average incubator chamber temperature has been obtained as* 34℃ *with a mean deviation of* 5℃. *The result reveals that the stored energy in the storage system is insufficient for sustaining the chamber temperature for 24hours. Therefore three kilograms of paraffin wax have been used additionally with 200Watts electric heater for the system. By doing this the result obtained from the system has been reached with an average eggs hatching ability of only 20% of the loaded eggs.*

Since thermal efficiency reduction of the system is affecting directly the hatchability of the eggs of the system; it is better to use an auxiliary heat source (like a PV subsystem).

***Keywords: -** Solar thermal incubator, Thermal storage medium, Paraffin wax, Egg Hatching*

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SYMBOLS AND NOMENCLATURE

I_{Sc}	*The solar constant (Watts/m²)*
σ	*The declination angle in degrees*
H_o	*The extraterrestrial daily radiation available*
$\emptyset$	*Latitude angle*
ω_s	*The solar hour angle in degrees*
Ns	*The maximum sunshine hour*
β	*Optimum Tilt Angle*
H	*The monthly mean daily solar radiation on a horizontal surface (MJ / m²)*
H_{bt}	*The daily beam radiation on an inclined surface (MJ / m²),*
H_{dt}	*The daily diffuse radiation on an inclined surface (MJ / m²),*
Hr	*The daily reflected radiation on an inclined surface (MJ / m²)*
$\dot{Q}_p$	*Solar energy absorbed by the solar collector absorber plate (Watts/m²)*
Q_L	*Heat loss of the collector (Watts/m²)*
$\dot{Q}_f$	*Heat absorbed by the fluid (Watts)*
$h_{c,pc}$	*The convection heat transfer coefficient between two inclined parallel plates (Watts/m²*K)*
F'	*Plate efficiency factor*
F_R	*The collector heat removal factor*
$\dot{m}$	*The air mass flow rate (kg/sec)*
$\dot{V}$	*The volume flow rate*
$\dot{m}$	*The mass of heat storage medium (kg)*
C_p	*The specific heat (kJ/kg*°C),*
Δhm	*The heat of fusion per unit mass (kJ/kg)*
Q_l	*Heat lost by conduction and convection of incubator walls*
Q_{egg}	*Quantity of heat required to raise the temperature of the egg*
Q_{vent}	*Heat lost through ventilation from the incubator chamber*
Qb	*The total heat load of the system*
$\bar{T}$	*Mean chamber temperature (℃)*
n_{eggs}	*Number of eggs*
Ns-	*Daylight length in an hour*
ns-	*Sunshine hour*
h_{ref}	*Reference enthalpy*

T_{ref}	*Reference temperature (℃)*

ABBREVIATIONS

HTF	*Heat Transferring Fluid*
T_{pw}	*The Paraffin Wax Temperature (℃)*
T_{ch}	*Chamber Temperature (℃)*
PCM	*Phase Change Material*
TES	*Thermal Energy Storage*
RH	*Relative Humidity*
LHS	*Latent Heat Energy Storage*
TESU	*Thermal Energy Storage Unit*

CHAPTER ONE
INTRODUCTION

1.1. Background

Energy is the primary and most universal measure of all kinds of work by human beings and nature. The utilization of solar energy in Ethiopia plays an important role in the future **[74]**. Solar thermal energy is the one source of free and renewable sources of energy that man can be captured for many different purposes. It is a very appropriate and low-cost system for rural and even for urban in developed as well as in developing countries for space heating and crop drying. The heat provided by solar energy also has been used successfully for many purposes. The concept of a solar thermal powered egg incubator by using solar thermal energy has been done by many researchers.

The works have been conducted by the researchers on these methods. **Enibe (2002)** designed, constructed, and evaluated the performance of a passive solar-powered air heating system. **Olayide *et al* (2007)** designed and constructed a solar incubator with a solar collector which heats water that in turn heats an incubating chamber for the process of fowl hatching. **Bolaji (2008)** has designed and constructed a solar poultry egg incubator by using materials that are readily available in the local market. In this study, the performance of the incubator has been evaluated. **Ojike *et al* (2020)** have conducted a study on the performance study of a solar poultry egg incubator with a phase change heat storage subsystem. It consists of the collector, storage, and incubating chamber.

Egg incubator is one of the inventions that provide opportunity, especially for a farmer. There is one of the easy and fastest ways that can make a product. This invention will upgrade the egg incubator that has already on market today. The systems will automatically control the temperature and humidity of the incubator for various types of eggs [**57]**.

Solar thermal energy is the source of heat for it. In this work, the performance of solar thermal powered eggs incubator has been studied under Adama, Ethiopia weather conditions. It has been the system designed instead of using natural incubation and electric power for this system. The system has been clean and not polluting the environment.

1.2. Statement of the problem

Many of the Ethiopian population are engaged in the small-scale agricultural sector and live-in rural areas. Energy is the key to economic and social developments. Poultry production is one the most important in nutrition, food security of the farmers and also it is the main source of income for the community **[74]**. It is mainly from traditional producers which are based on a broody hen.

Eggs incubation is performed traditionally by natural incubation and electric powered incubator. Natural egg incubation is performed by using the body heat of broody hen and the latter is by electricity. Broody hens naturally can incubate their eggs without any cost. However, they can only incubate of maximum up to twelve (12) eggs at a time and merely sometimes they can also be dying by accident or diseases while incubating their eggs. They can’t produce in mass numbers.

A lot of poultry hatching eggs are artificially incubated in incubators that must be designed to control the temperature inside the machine to ensure that the temperature of the developing embryo **[62]**. An egg incubator has been the chamber or space that holds eggs while maintaining an appropriate temperature, humidity, and oxygen level. Temperature is one of the most important physical factors that Affect eggs incubation and embryonic development. Access to energy plays a larger role to sustain the life of the people. Currently, the cost of energy increasing, and this encourages the researchers to other sources of energy like conventional sources of energy.

Hence, searching for a free, alternative, and reliable supply of energy has been very important for poultry production. This works designs, constructs, and studies the performance of solar-powered incubators with thermal storage.

1.3. Objectives

1.3.1. General Objective

The main objective of this work is to design, construct, and evaluating the performance of a solar thermal chicken egg incubator with thermal energy storage under Adama, Ethiopia weather conditions.

1.3.2. Specific Objectives

The specific objectives of this project are:

- ✓ To design the solar thermal chicken egg incubator for 200 eggs,
- ✓ To design the solar air heater and thermal energy storage unit for the system,
- ✓ To construct the model of solar thermal incubator with solar air collector and thermal energy storage, and
- ✓ To evaluate the performance of the solar thermal powered chicken egg incubator under Adama weather conditions.

1.4. Significance

The main significance of the study is using the freely available solar thermal energy for chicken egg incubation purposes. This work may help the community as:

- ➭ It promotes small-scale poultry producers to use free and alternative forms of energy for their backyard poultry production.
- ➭ Since the system is economical, cost-effective, and less effort low-income communities and beginner poultry producers can easily access it.

1.5. Scope of the study

The focus of this work is to design and construct, and evaluate the performance of a solar thermal powered incubator for hatching eggs under Adama weather conditions. The model of a solar thermal powered incubator chicken egg incubator is constructed, and the performance has been evaluated.

1.6. Thesis Outlines

The work has been divided into seven chapters. This paper presents the performance of solar thermal powered chicken eggs incubator, conclusion, and recommendations, resulted from experiments. Each chapter of the work was defined as the following:

Chapter 1 Introduction: This chapter provides an introduction and brief background required to get a better understanding of this works as a guide for the rest of the document. In addition to that, the objectives and problem statement for the work have been defined.

Chapter 2 Literature Review: This chapter contains some relevant information and findings resulted from the inclusive literature review and operational principles used in this study have been stated.

Chapter 3 Materials, Methodology, and Data Collection: This chapter describes the data used and the parameter that governs the system operation. Also in this chapter, the equations and formulas used to model the system energy load has been presented.

Chapter 4 Experimental setup and Measurement Procedure: In this chapter, the whole components experimental setup of the system and experimental procedures are defined.

Chapter 5 Result and Discussion: This chapter presents the results and discussions from the experimental work. This chapter also comprises the investment cost and equipment life cycles findings.

Chapter 6 Conclusions and Recommendations: This chapter describes the conclusions and recommendations based on chapters two and five.

CHAPTER TWO
LITERATURE REVIEW

2.1. Introduction

This chapter presents the works of literature and a summary of the literature's done recently on egg incubation and the solar thermal systems.

2.1.1. Egg incubation

Incubation is the process by which the embryo within the egg develops into a fully formed chick capable of breaking free from the shell. Incubating eggs requires several important environmental considerations if any chicks are to hatch. Of primary concern are temperature and relative humidity. The incubation process is divided into two types. They are natural and artificial egg incubation.

Natural incubation uses a broody hen to incubate eggs by sitting on them in a nest. It involves a transfer of heat between the parent and embryo. Broody hens, when available, work best for small clutches of eggs. Broodiness, the behavior of a setting hen, has been bred out of some chickens. Many domestic bird varieties also make good mothers, but the consideration is their size.

Figure 2.1 Natural incubation

Larger breeds can easily incubate up to twelve large chicken eggs, 10 duck eggs, or 5 goose eggs. They may be able to incubate only six large chicken eggs and would not be useful to incubate duck or goose eggs.

An artificial incubator is a man-made device that is designed to artificially create the natural conditions that a hen creates whilst sitting on her eggs.

Figure 2.2 Artificial Incubation

They have a heat source device that keeps a constant temperature, and water pans under the eggs trays to control the amount of moisture in the incubator and eggs turning mechanism.

2.1.2. Design Parameters of Artificial Incubation

Four factors are of major importance in incubating eggs artificially: temperature, humidity, ventilation, and turning. Of these factors, the temperature is the most critical. However, humidity tends to be overlooked and causes many hatching problems. **Temperature:** The acceptable range is 35.5 to 39℃. If the temperature stays at either extreme for several days, the eggs may not hatch. Overheating is more critical than underheating. Running the incubator at 40℃ for 15 minutes will seriously affect the embryos while running it at 35℃ for 3 or 4 hours will only slow the chick's metabolic rate **[61]**. **Humidity:** The relative humidity of the air within an incubator should be about 60 percent. During the last 3 days (the hatching period) the relative humidity should be nearer 65-70 percent. Too much moisture in the incubator prevents normal evaporation and results in a decreased hatch, but excessive moisture is seldom a problem in small incubators. Too little moisture results in excessive evaporation, causing chicks to stick to the shell, remain in the piped shells and sometimes hatch crippled. The relative humidity in the incubator can also be varied by changing the size of the water pan or by putting a sponge in the pan to increase the evaporative surface.

The pan should be checked regularly while the incubator is in use to be sure that there is always an adequate amount of water. Adding additional water pans to small still-air incubators is also helpful to increase humidity **[61]. Ventilation:** The best hatching results are obtained with normal atmospheric air, which usually contains 20-21 percent oxygen. It is difficult to provide too much oxygen, but a deficiency is possible. Make sure that the ventilation holes are adjusted to allow a normal exchange of air. This is critical for homemade incubators. It is possible to suffocate the eggs and chicks in an air-tight container. However, excessive ventilation removes humidity and makes it difficult to heat incubators properly **[61]. Turning:** Eggs set on their sides must be rotated 1/2 turn at least 3 times daily. Eggs set with the air cell end up should be tilted in the opposite direction 3 times daily. This keeps the embryo centered in the egg and prevents it from sticking to the shell membrane. Stop turning the eggs for the last three (3) days of the incubation cycle (at 18 days for chickens) **[61]**.

2.1.3. Incubator Operation

Maintain the temperature range between $37 - 38\ ℃$ if possible. The thermometer is used to measure the temperature at a level or slightly above where the center of the egg. Overheating the embryo is much more damaging than is under heating it, overheating speeds up embryo development, lowers the percentage of hatch-ability, and causes abnormal embryos. Although a short cooling period may not be harmful, longer periods of low temperatures will reduce the rate of embryo development. Excessively low temperatures will kill the embryos. If the temperature remains beyond either extreme for several days, hatch-ability may be severely reduced. The moisture level in the incubator should be about 50 to 55 percent with an increase to about 65 percent for the last 3 days of incubation. Moisture is provided by a pan of water under the egg tray. Ventilation is adjusted by increasing or decreasing openings in the sides or top of the incubator. Normal air exchange is needed during embryo development and should be increased as the chicks begin to hatch [**20]**.

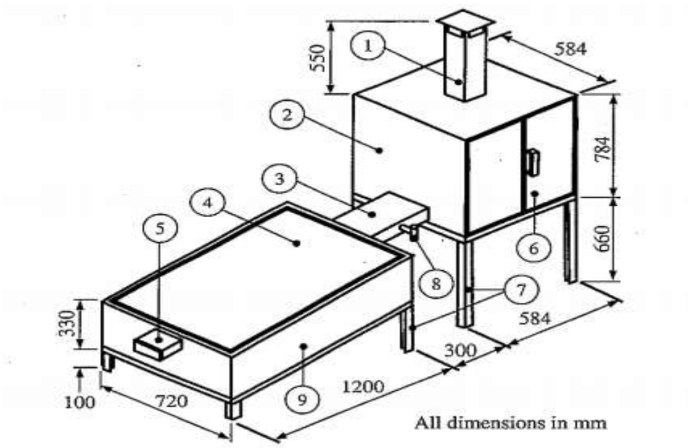
2.1.4. Reviews on Solar thermal Powered Egg Incubator

Verlumun (1991) designed and constructed a passive solar heated poultry eggs incubator. This passive solar-powered air-heated poultry eggs incubator of 150 eggs capacity and consists of a solar collector, thermal storage unit, and the incubating cabinet. Temperature control within the range of $37.6℃ \pm 0.8℃$ is by use of a 24V, 150Amps hour lead acid battery-operated solenoid valve, in addition to an ether-filled contact thermostatic switch. A spring-loaded pressure relief valve is incorporated to avoid pressure buildup in the system.

Enibe (2002), designed, constructed, and evaluated the performance of a passive solar-powered air heating system. The system, which has potential applications in crop drying and poultry egg incubation, consists of a single-glazed flat plate solar collector integrated with a phase change material (PCM) heat storage system. The PCM is prepared in modules, with the modules equip-spaced across the absorber plate. The results show that the system can be operated successfully for crop drying applications. With suitable valves to control the working chamber temperature, it can also operate as a poultry egg incubator.

Olayide *et al* (2007) designed and constructed a solar incubator with a solar collector which heats water that in turn heats an incubating chamber for the process of fowl hatching. It is designed to work for 24 hours and it has a built-in heat storage facility that supplies heat to the incubating chamber during the day that there is no solar energy. The working (water) is heated in the solar collector and transported (circulated) by the thermosiphon process through the pipes.

Bolaji (2008) designed and evaluated the performance of the solar poultry egg incubator. This incubator consists of a solar collector with built-in thermal storage and an incubator chamber of 100 eggs capacity. Its average outlet collector temperature has been $72.4℃$ for the highest solar radiation day and $51.8℃$ has been obtained on the lowest solar radiation day. Its thermal efficiency has been found at 68.7%.



1. Chimney
2. Incubator chamber
3. Air outlet duct
4. Transparent glass cover
5. Air inlet duct
6. Cabinet door
7. Stands
8. Air regulation
9. Solar collector

Figure 2.3 Solar thermal poultry egg incubator, [Bolaji, 2008]

Victor *et al* (2015) designed, developed, and evaluated a Passive Solar Poultry Egg Incubator. The system had two heat collectors and storage media (thermal masses) and heat exchangers. The main heat absorber has been made of 80mm thick concrete incorporated with a separate heat storage media to serve as backup during sunless hours. The temperature maintained in the incubating chamber ranged between 30.9– 46.6℃ depending on the time of the day and weather conditions. At an average ambient relative humidity of 69.2%, the incubating chamber relative humidity has been averagely at 61.6 %, using activated charcoal as dehumidifying material. Heat collection and transfer efficiencies of the thermal mass were 96.4% and 44.3%, respectively.

Kanu *et al* (2016) constructed and characterized the solar-powered micro-based incubator for the chicken egg. It consists of a solar collector which heats water that in turn heats an incubating chamber for the process of hen hatching. It is designed to work for 24 hours and has a built-in heat storage facility that supplies heat to the incubating chamber when there is no solar energy. This micro-based solar incubator has been able to hatch eggs within 20-21 days. This work used materials from the local market.

Uzodinma *et al (*2019) conducted the performance study of a solar poultry egg incubator with a phase change heat storage subsystem. This study evaluates the performance of a hybrid solar-powered poultry egg incubator. The system consists of a double-glazed flat plate solar collector integrated with a paraffin type phase change material energy storage subsystem and incorporated with a PV subsystem. Results of the study showed that the chamber temperature has been within the range of between $36 - 39$ ℃ and relative humidity of 50 – 75%.

The temperature ranges were between $42 - 106$℃ and $38 - 99$℃ respectively were observed at the storage medium and absorber plate with an average egg hatchability of 62.37% using the hybrid solar-powered poultry egg incubator.

2.1.5. The Effects of Low and High Temperature on Embryonic Development and Hatch

SUAREZ *et al (*1996) experiment on Low-Temperature Effects: On Embryonic Development and Hatch Time. A series of experiments have been conducted to estimate phenotypic correlations between incubation characteristics, and to evaluate the effects of cold stress and genotype during incubation on chick weight, egg weight loss, hatching time, and embryonic mortality. Results indicated a low and negative correlation between hatching time and chick weight.

Willemsen *et al (*2010), conducts a study on the effects of High and low-temperature manipulation during late incubation and embryonic development, the hatching process, and metabolism in broilers. They conclude that the growth of embryos exposed to higher incubation temperatures during the latter part of incubation reduced. In addition, they conclude hatch-ability has been significantly reduced by the high-temperature treatment due to higher embryonic Mortality. Although the hatching process of embryos exposed to lower incubation temperatures has been also significantly retarded their embryonic development and growth.

2.2. The System Components

2.2.1. Solar Collector

Solar collectors are a device for collecting solar radiation and transfer the thermal energy to fluid (HTF) passing in contact with it. The utilization of solar energy requires solar collectors. The solar energy collector, with its associated absorber, is the essential component of any system for the conversion of solar radiation into a more usable form. The flat plate collector is the most important type of solar collector because it is simple in design, has no moving parts, and requires little maintenance. It can be used for a variety of applications in which the temperature of required heat energy ranges from $40 - 100$℃.

Enibe *et al* (2003) have conducted an experimental and thermal analysis of a natural circulation solar air heater with phase change material energy storage. The system consists of a single glazed flat plate solar collector integrated with a paraffin type phase change material (PCM) energy storage subsystem and a rectangular enclosure that serves as the working chamber. They compare the predicted performance of the system with experimental data under daytime no-load conditions over the ambient air temperature range of $19 - 41$℃. The maximum temperature difference between predicted and experimental results at specific locations on the absorber plate, heat exchanger plate, glazing, and heated air is 10, 6, 8, and 10℃.

Kumar *et al* (2014) had made an experimental analysis on Solar Air Dryer. An indirect forced convection solar dryer is designed and fabricated to investigate its performance under the hot and dry climatic conditions of Jaipur, India. The system consists of a flat plate collector and drying chamber with two shelves and a chimney. Dimensions of collector and drying chamber are 1.21 mx0.87 m and 0.5x0.5x0.5m respectively. There are four baffles of dimension 40cmx3cmx7cm fitted between absorber and backplate. The distance between the backplate and absorber plate is 8cm. The experiments were performed on green chilies. The drying time is 10 hours. The collector is inclined at 45° with horizontal and oriented in the South-North direction. During experimentation 11btemperatures, relative humidity, air velocity, and solar intensity were measured hourly in May and July 2010 for drying of green chilies and potato chips. The solar intensity varied between 550-890 W/m^2 and the maximum temperature rise has been 20℃.

Figure 2.4 Solar air Dryer, (**Kumar et al, 2014)**

Experiments were performed on a solar air heater; the maximum temperature rise is 20°c and the maximum solar intensity has been 890W/m^2.

Kalaiarasi *et al (*2019) have studied experimental analysis and comparison of flat plate solar air heaters with and without integrated sensible heat storage. Both the SAHs were tested for three different mass flow rates (0.017 kg/s, 0.02 kg/s, and 0.028 kg/s) at one of the hottest cities in India, Madurai. The results show that the novel SAH had operated at a maximum efficiency of 67.7% when the mass flow rate has been 0.028 kg/s before the solar radiation started to decrease around 14hr Indian standard time. It also concluded that sensible heat storage at the absorber plate improves the thermal output, therefore leads to consistent performance.

Abuşka *et al* (2019) have experimented with performance evaluation of solar air collectors with PCM honeycomb combination under the natural convection. In the experiments, the heat storage material has been tested in two forms with 26 kg capacity, PCM with honeycomb core in the first collector (type I) and only PCM in the second collector (type II), and the third collector (type III) with a flat absorber plate for comparison. The first collector reached the PCM melting point about 50 min ago. Also, when we consider the peak point, an apparent 10°C advantage is achieved in sensible heat storage in favor of type I.

Figure 2.5 Experimental Set up of solar air collector with PCM honeycomb combination under the natural convection **[Abuşka *et al,* 2019]**

It is observed that the honeycomb core used as a heat transfer enhancer is effective in shortening the charge-discharge times, also a noticeable difference in sensible heat storage during the noon. The production of useful energy in Type I lasted 469 min and 539 min longer than type III, respectively. The thermal efficiencies under daylight were calculated as 10.1%, 10.9%, and 13.6%, respectively. As a result, it can be said that the use of honeycomb core as heat conductivity enhancer material is very functional, during the discharge period.

Kurtbas *et al* (2006) have experimentally investigated the Solar Air Heater performance with Free and Fixed Fins. In this study, each of the fins, which are in the form of rectangular having two different surface areas, is located on the absorber surface in free and fixed manners. In the first case, the fins are located on the absorber surface in a way to be able to freely move. In the second case, it has been fixed to the absorber surface. The absorber surface area (A) is 1.64 m^2. The fixed and free fins with 8 and 32 items whose surface areas (A_f) are 0.048 and 0.012 m^2 are located on the absorber surface. Thus, the total fin area in the absorber surface is equaled (0.384m^2).

2.2.2. Solar thermal energy storage

Energy storage can reduce the time or rate mismatch between energy supply and energy demand, thereby playing a vital role in energy conservation. It improves the performance of energy systems by smoothing and increases reliability.

In the solar thermal system because of the intermittent availability of solar radiation the thermal energy storage has been very important during the night time and cloudy time. Therefore, the design and development of efficient and economical thermal energy storage systems are of very importance. Thermal energy can be stored as a change in the internal energy of a material as sensible heat, latent heat, or thermochemical.

2.2.2.1. Sensible heat storage

Sensible heat storage materials undergo no phase change within the temperature range required for the storage application. In sensible heat storage thermal energy is stored by raising the temperature of a solid or liquid. A sensible heat storage system utilizes the heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of heat stored depends on the specific heat of the medium, the temperature change, and the amount of storage material.

$$Q = \int_{T_i}^{T_f} mCpdT = mC_{cp}(T_f - T_i) \quad \ldots \ldots \ldots \ldots (2.1)$$

Within the indicated solids, concrete and cast ceramics have been extensively studied due to their low costs and good thermal conductivities, despite their moderate specific heats.

This heat is released in the respective discharging process. There are some advantages for SHS compared to LHS at high temperatures including simplicity of design and construction, ease of control, and hence lower cost **[8]**.

2.2.2.2. Latent Heat Storage

Latent Heat Storage, which stores or releases energy during a phase change (solid, liquid, gas). If the material changes its phase at a certain temperature while heating the substance, then heat is stored in the phase change. Reversing, heat is dissipated when at the phase change temperature, it is cooled back. Among the various methods of energy, latent heat thermal energy storage is particularly attractive.

The motivation for using phase change materials (PCM) is their high energy storage density and their ability to provide heat at a constant temperature **[9]**. The storage capacity of the LHS system with a PCM medium is given by:

$$Q = \int_{Ti}^{Tm} m * Cp * dT + m * \Delta h_m + \int_{Tm}^{Tf} m * Cp * dT \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

where: Q is the amount of thermal energy stored or released in form of sensible heat (kJ), T_i is the initial temperature in (°C), T_m(°C) is the melting temperature (°C), T_f (°C) is the final temperature, m (kg) is the mass of heat storage medium (kg), Cp (kJ/kg°C) is the specific heat (kJ/kg°C) and Δh_m is the heat of fusion per unit mass (kJ/kg) **[65]**.

2.2.3. Thermal Energy Storage Performance and Characterization

Latent heat storage in the temperature range $0 - 120$℃ is of interest for a variety of low-temperature applications, such as space heating, domestic hot water production, heat-pump assisted space heating, greenhouse heating, solar cooling, etc. **[8]**.

2.2.3.1. Reviews on LHTS Charging/Discharging Enhancement

Heat transfer rate increases with contact surface area between PCM and heat transferring fluid (HTF). For encapsulating the PCM in small casings, the contact surface with HTF is increased to compensate for the poor thermal conductivity of the PCM.

Additionally, it serves below two purposes: (1) it prevents phase segregation and sedimentation, and (2) it offers a high ratio of area for heat transfer to volume [**16]**.

Pradeep *et al* (2016) had made a review on how LHTS heat transfer has been enhanced and concluded that the use of fins provides a larger heat transfer surface area thereby promoting faster melting and solidifying rates. The conduction process followed by Convection promotes the melting of PCM as energy is absorbed. Hence the design of the TES must be in such a way that the melting and freezing process are improved and a proper PCM with the required properties are selected for the effective performance of the thermal storage system.

Halawa and Saman (2011) had made a numerical study on the performance of PCM-based TES for space heating applications. The storage unit has been made of 45 rectangular slabs of length 1m and width 0.89m. The numerical investigation has been conducted with variations in the thickness of the PCM slab and air gaps between the slabs.

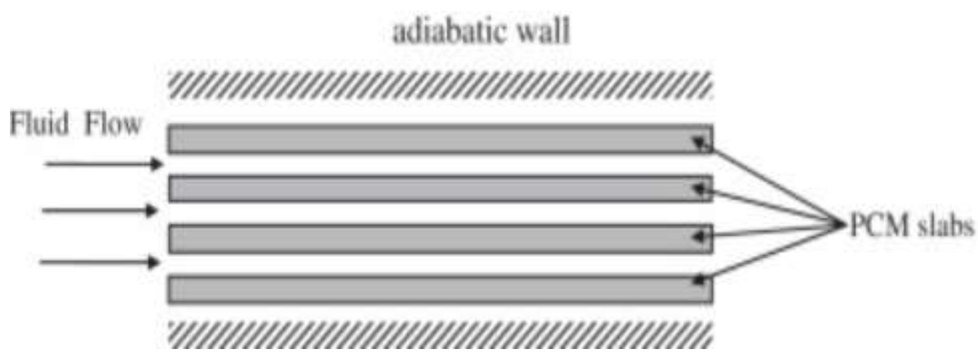


Figure 2.6 The TSU modeled [**15]**

The results of the experiment show that the thickness of the slab had an impact on the heat transfer rates. Thicker slabs reduced the heat transfer rates which led to the increased melting and freezing time, but with a higher mass flow rate, the melting and freezing time has been reduced.

2.3. Literature Summary and the Research Gaps

The following summary describes previous research work on the study of the performance of solar thermal powered egg incubators: -

Review Performance of Solar Thermal Powered Egg Incubator				
S/N	Title	Authors	Capacity	Components &Results
1	Design and Construction of a Passive Solar Heated Poultry Eggs Incubator.	[Verlumun, 1991]	Egg's incubator of 150 eggs	Solar Collector, Thermal Storage Unit and The Incubating Cabinet
2	Design, construction, and evaluating the performance of a passive solar-powered air heating system	[Enibe, 2002]	Has the potential applications in crop drying and poultry egg incubation	Single-Glazed Flat Plate Solar Collector (PCM) Heat Storage System
3	Design and construction of the solar incubator	[Olayide *et al*, 2007]	Solar Collector Transported (Circulated) Fluid by Thermo Siphon Process	Solar Collector Heat storage (Water)
4	Design And Evaluate the Performance of The Solar Poultry Egg Incubator	[Bolaji, 2008]	Chamber has 100 eggs capacity	Solar collector Thermal storage Incubator chamber The average Outlet Collector Temperature has been 72.4℃ and 51.8℃ The system thermal efficiency has been found 68.7%
5	Design develops and evaluates the performance of a Passive Solar Poultry Egg Incubator	[Victor *et al*, 2015]	Multi-functional system (For egg incubation and crop drying)	Two heat collectors and Storage media (thermal masses) Heat exchangers Heat collection efficiencies are 96.4% Heat transfer efficiency is 44.3%
6	Construction and characterization of the solar-powered micro-based incubator for	[Kanu *et al*, 2016]		A solar collector Thermal storage (water) Incubating chamber

	chicken egg			
8	Performance study of a solar poultry egg incubator with phase change heat storage	[Uzodinma *et al*, 2019]		Phase change material energy storage PV subsystem A double-glazed flat plate solar collector The chamber temperature has been between $36-39$ ℃ and Relative humidity of 50–75% Average egg hatch-ability of 62.37%
9	Characterization of A Photovoltaic Powered Poultry Egg Incubator	[Okonkwo *et al*, 2012]	Capable of handling up to 375 eggs	A power supply unit, an energy or photovoltaic (PV) Storage unit and the egg Incubation chamber Temperature $36-39$℃ Relative humidity $77-67\%$

The works of literature show that solar thermal energy is the freest and low-cost system that is used for different purposes especially for space heating and crop drying. The researchers reviewed in this study were attempted to use solar thermal energy for egg incubation.

The system has three main components. These are solar air heater (flat plate solar collector), thermal energy storage unit, and chamber. In the literature, it is observed that the mainly used thermal energy storages are paraffin wax, water, and stones pebbles as both sensible and latent thermal storage. Among them, paraffin wax is the one mostly used for solar thermal eggs incubator systems for it is high energy density and stability during energy gaining and discharging.It is also observed that the systems mainly depend on the time of the day and weather conditions. The ambient air temperature is the main condition affecting the system's operation. The low ambient air temperature results in high heat loss from the system; hence, the low thermal efficiency of the system.

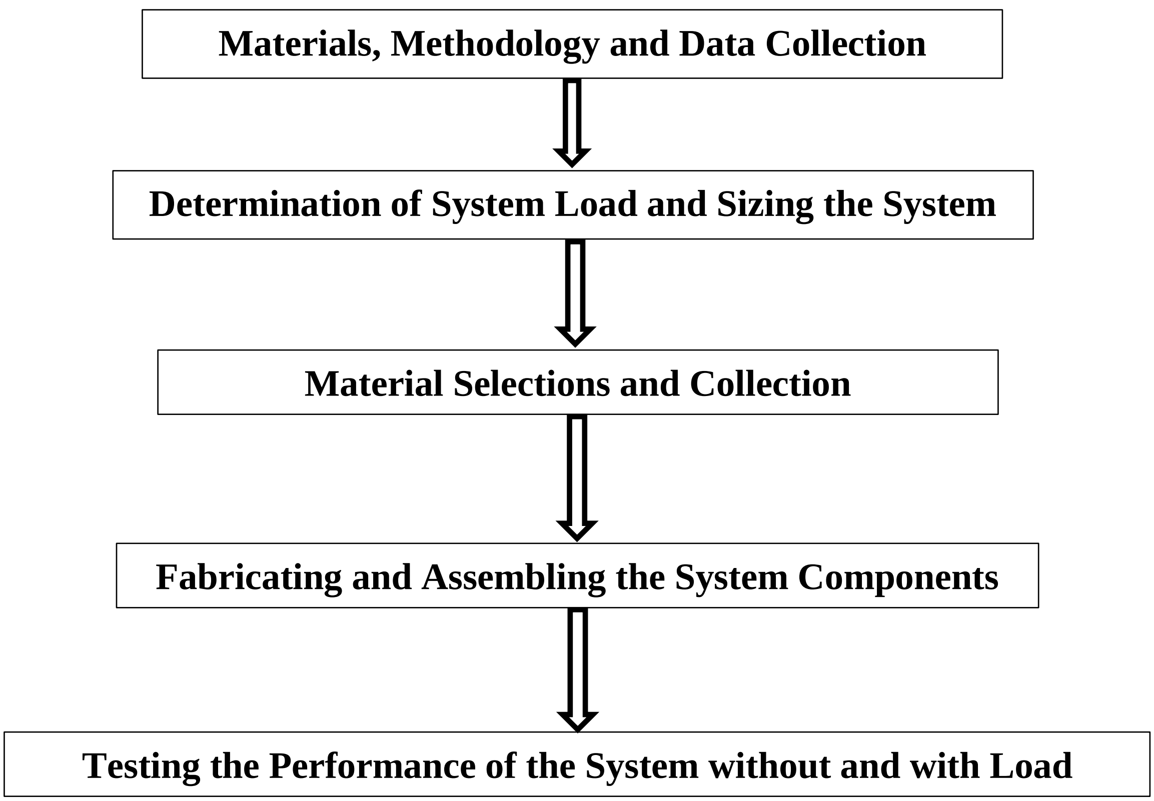
The literatures also illustrates that poultry production is a beneficial business in Ethiopia especially in most rural of the country. The few commercially type poultry productions are around Addis Ababa and far from most. The main part of the country has no access to the electric grid system but most of the poultry productions are from there. Therefore, this work will be done to study the performance of solar thermal energy for chicken eggs incubator under Adama Town, Ethiopia weather conditions.

CHAPTER THREE

METHODOLOGY, MATERIALS, AND DATA COLLECTION

3.1. Methodology

In this section, the methods to maintaining the system parameters governing the system operation and the whole principles followed to do the work are discussed. Many theoretical and experimental works have been done to reach the objectives. And many related studies and books are used as the reference for accomplishing the system. The following lists are the methodology and steps carried out by the work to achieve the aims.



3.2. Data Collection

The data used in this study has been having primary and secondary data. The primary data is calculated from the system load. The secondary data has been derived from the primary data. They are the total average sunshine hours for each month, the average daily temperatures, latitude, and altitude. Those are discussed as follows:

3.2.1. Solar Potential Data of Adama Town

In this section, the solar potential of Adama town has been estimated. Solar energy consists of two parts: extraterrestrial solar energy which is above the atmosphere and global solar energy which is under the atmosphere. The measured solar energy values can be used for developing solar energy models which describe the mathematical relations between solar energy and meteorological variables such as ambient temperature, humidity, and sunshine ratio. Solar energy of daylight utilization for any site is dependent upon the quality of the available flux **[49]**. The solar radiation, through the atmosphere, reaching the earth's surface can be classified into two components: beam radiation and diffuse radiation. Beam radiation is the solar radiation propagating along the line joining the receiving surface and the sun. It is also referred to as direct radiation [63].

Most of the radiation estimates are made in terms of the ratio of available radiation (H) to the theoretically available radiation outside the atmosphere (H_0). The radiation available outside the atmosphere which is also known as extraterrestrial radiation is calculated from the most commonly used relation given.

$$H_0 = \left(\frac{24}{\pi}\right) * I_{sc} * \left(1 + 0.033 * \cos\left(\frac{360n}{365}\right)\right) * \left(cos\emptyset cosd sin\omega + \frac{2\pi}{360}\omega sin\emptyset sin\sigma\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

where I_{Sc} is the solar constant; n is the day of the year (starting at 1 for January 1); l is the latitude in degrees; σ is the declination angle in degrees,ω is the sunset hour angle in degrees and H_o is the extraterrestrial daily radiation available outside the atmosphere on a horizontal plane. For all the calculations a value of $1367\ W/m^{2}$ is used for I_{sc}. This parameter includes:

3.2.1.1. Location

Table 3.1. Latitude, Longitude, and Altitude of Adama Town

Location	Latitude	Longitude	Altitude
Adama	8°32′N	39°22′E	1648m

Where: $\emptyset = 8.533°$ (latitude angle)

3.2.1.2. The declination angles

The declination δ is the angular position of the solar noon concerning the plane of the equator, and has been calculated by the formula proposed by (Cooper, 1669) as follows:

$$Declination\ angle\ (\delta) = 23.45 * sin\left(\frac{360}{365} * (284 + n)\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3.2)$$

3.2.1.3. The Relative humidity

Table 3.2. the average relative humidity of Adama city.

Months	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Average of RLH	45.48	53.28	50.09	47.76	59.06	48.29	62.23	68.18	65.55	58.03	48.42	49.00

3.2.1.4. The Sunshine Hours on Horizontal Surface

$$\omega_s = (2/15) * \cos^{-1}(-\tan\emptyset \tan\delta) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3.3)$$

Where ω_s is the solar hour angle (ω) corresponding to the time when the sunsets. Since the solar hour angle (ω) is the angular displacement of the sun east or the west of the local meridian; morning negative afternoon positive. The solar hour angle is equal to zero at solar noon and varies by 15° per hour from the solar noon. The sunset hour angle (ωs) has been computed by the following equation: **[Venkatachalam et al, 2019]**

The maximum sunshine hour will be: $Ns = \frac{2}{15}\omega_s$

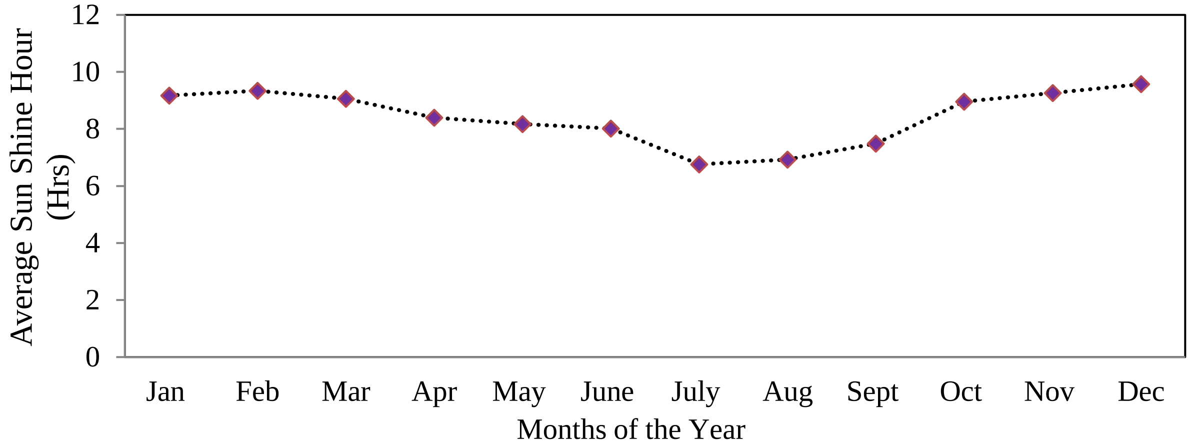


Figure 3.1 Sun Shine Hour and the average monthly sunshine hour (ns) of Adama Town

For the surface facing due south, the incident is calculated as:

$$cos\theta_i = \cos(\emptyset - \beta)\, cos\delta cos\omega + sin\delta \sin(\emptyset - \beta) \ldots\ldots\ldots\ldots \quad (3.4)$$

3.2.1.5. Optimum Tilt Angle (β)

The efficiency of a solar is highly dependent on the amount of solar radiation received by the collector surface. This way, solar collectors must be inclined at ideal angles to gather the most extreme solar energy accessible in particular locations.

$$tan\beta = \frac{-\sin(\delta)\cos(\emptyset)\cos(\gamma) + \cos(\delta)\sin(\emptyset)\cos(\gamma)\cos(\omega) + \cos(\delta)\sin(\gamma)\sin(\omega)}{\sin(\delta)\sin(\emptyset) + \cos(\delta)\cos(\emptyset)\cos(\omega)} \ldots\ldots \quad (3.5)$$

3.2.2. Monthly Average, Daily Global Radiation

The correlation for estimating the monthly average daily total (global) radiation on a horizontal surface can be given as [70],

$$\frac{\overline{H}}{\overline{H}_O} = a + b\left(\frac{\overline{n_s}}{\overline{N_s}}\right) \ldots\ldots\ldots\ldots \quad (3.6)$$

Where:

$$a = -0.110 + 0.235cos\emptyset + 0.323\left(\frac{\overline{n_s}}{\overline{N_s}}\right)$$

$$b = 1.449 - 0.553cos\emptyset - 0.694\left(\frac{\bar{n}_s}{\bar{N}_s}\right)$$

Where: H is the monthly mean daily solar radiation on a horizontal surface (J/m^2)

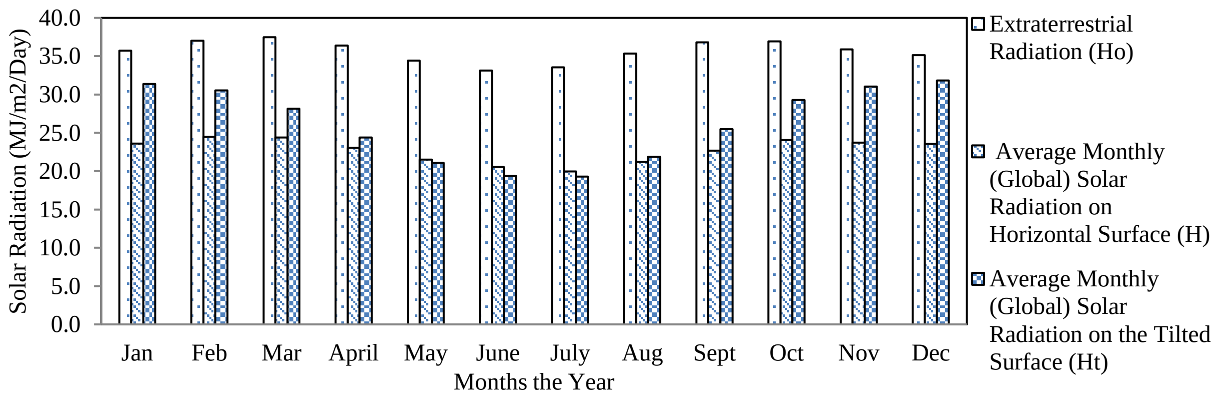


Figure 3.2 The Monthly Extraterrestrial, average daily total (global) solar radiation on horizontal and the average daily total on the tilted surface at $\mathbf{25°}$ solar radiation

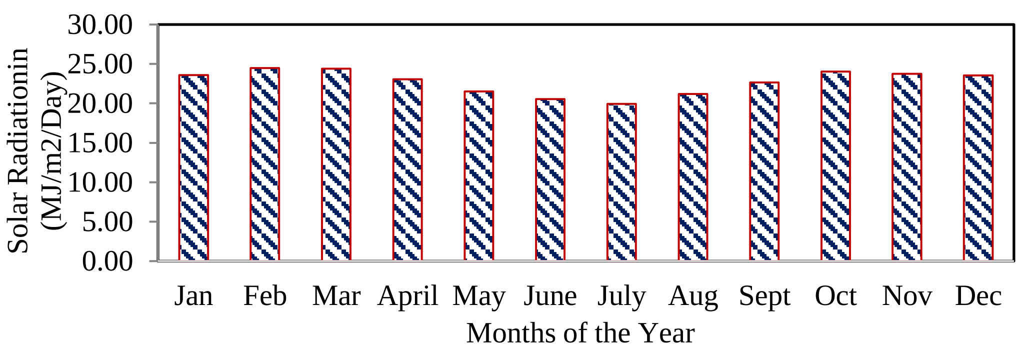


Figure 3.3 The average daily total (global) radiation of Adama Town

The solar radiation, through the atmosphere, reaching the earth's surface can be classified into two components: beam radiation and diffuse radiation. Beam radiation is the solar radiation propagating along the line joining the receiving surface and the sun. It is also referred to as direct radiation.

3.2.2.1. Estimation of Daily Global Solar Radiation on a Horizontal Surface (H)

Daily global radiation on a surface is the average of the hourly global radiation on a surface that may be found with the following equation: **[34]**

$$H = H_b + H_d \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (3.7)$$

Where H_H *is* the daily global radiation on a horizontal surface, H_b is the beam radiation on a horizontal surface and H_d is the diffuse radiation on a horizontal surface.

$$Kt = \frac{H}{H_o}$$

Ho is daily extraterrestrial radiation (MJ/m^2/Day) which is found with equation (1). Lam and Li's Model provide a correlation between global solar radiation and its components as follows: **[34]**

Where: $Kt = \frac{H}{H_o}$

$$for\ 0 < Kt \leq 0.15 \qquad H_d = (0.977) * H$$

$$for\ 0.15 < Kt < 0.17 \qquad Hd = (1.237 - 1.361Kt) * H$$

$$for\ 0.17 < Kt \leq 0.15 \qquad H_d = (0.273) * H$$

Diffuse radiation is the solar radiation scattered by aerosols, dust, and molecules; it does not have a unique direction.

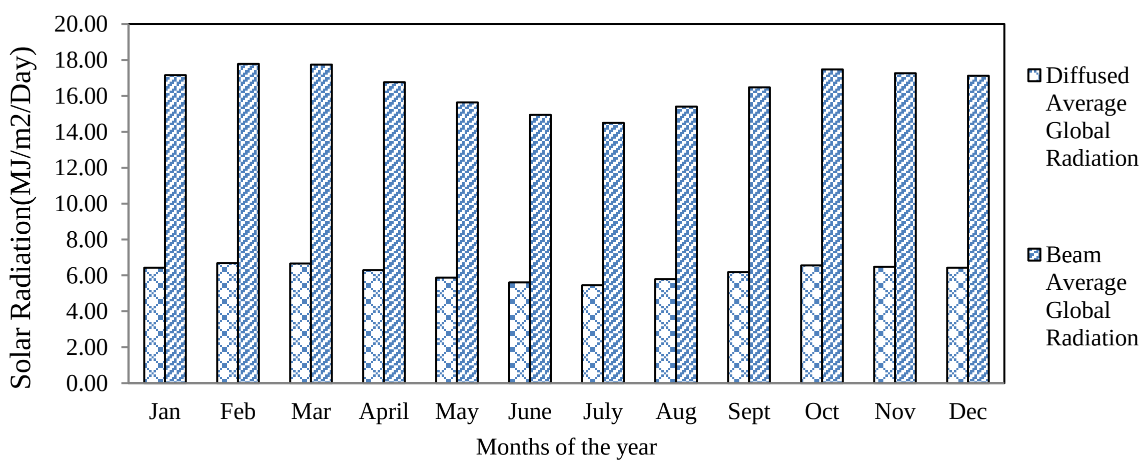


Figure 3.4 The beam and diffused solar radiation of Adama Town

3.2.2.2. Monthly Average Hourly Global Radiation on a Horizontal Surface

$$\bar{I} = \bar{H} * \frac{\left(\frac{\pi}{24 * 3600}\right)(a1 + b1 * cos\omega)(cos\omega - cos\omega s)}{(sin\omega s - \left(\frac{\pi}{180}\right) * \omega s * cos\omega s)}$$

Where $\bar{I}$ - monthly average hourly global radiation on a Horizontal Surface

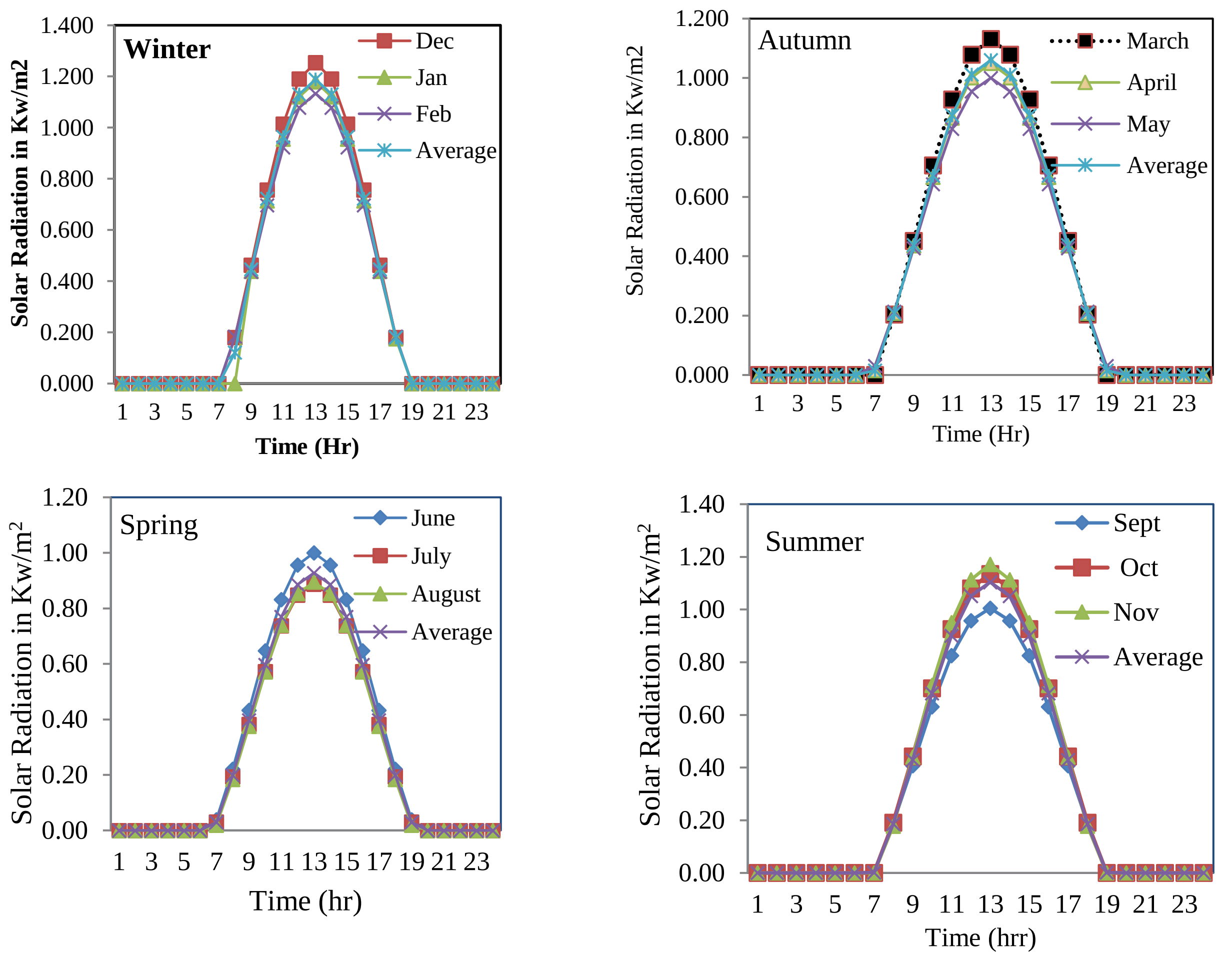


Figure 3.5 Monthly average hourly global radiations on a horizontal surface in kw/m^2

3.2.2.3. Daily Global Radiation on an Inclined Surface

Daily global radiation on an inclined surface can be found with the following equation: **[34]**

$$H_t = H_{bt} + H_{dt} + H_r \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.8)$$

Also, it can be written as:

$$H_t = H_b * R_b + H_d * \left(\frac{1 + cos\beta}{2}\right) + H_r * \rho_g * \left(\frac{1 - cos\beta}{2}\right) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (3.9)$$

Where H_{bt} is the daily beam radiation on an inclined surface, H_{dt} is the daily diffuse radiation on an inclined surface, and Hr is the daily reflected radiation on an inclined surface.

Where:

$$H_{bt} = R_b * H_b \dots\dots (3.10)$$

$$Rb = \frac{\left(\frac{\pi}{180}\right)\omega_{s'} sin\delta \sin(\emptyset - \beta) + cos\delta \cos(\emptyset - \beta)\, sin\omega_{s'}}{\left(\frac{\pi}{180}\right)\omega_s * sin\delta sin\emptyset + cos\delta cos\emptyset sin\omega} \dots\dots (3.11)$$

ω'_s is the sunset hour angle for an inclined surface (in degrees) and is given by

$$\omega'_s = \min\{\omega_s, cos^{-1}[-tan\delta \tan(\emptyset - \beta)]\} \dots\dots (3.12)$$

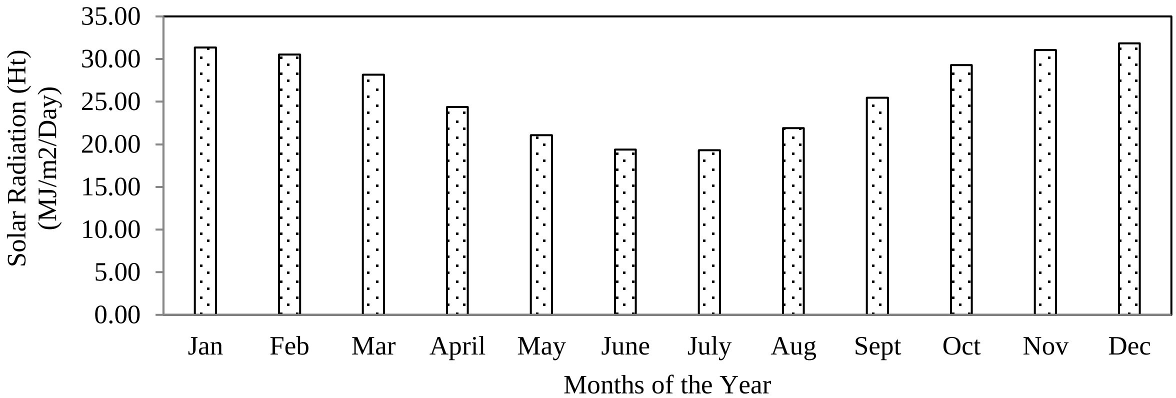


Figure 3.6the Average Total Solar radiation on Collector surface

The total solar radiation on the tilted surface for an hour as the sum of three terms shown as follows: **[70]**

$$It = Ib * Rb + Id * \left(\frac{1 + cos\beta}{2}\right) + I * \rho g * \left(\frac{1 + cos\beta}{2}\right) \dots\dots (3.13)$$

From Erb's correlation it can be written as:

$$\mathrm{R} = \frac{I_t}{I} = \frac{Ib}{I} * Rb + \frac{Id}{I} * \left(\frac{1 + cos\beta}{2}\right) + \rho_g * \left(\frac{1 + cos\beta}{2}\right) \dots\dots (3.14)$$

Where:

$$Rb = \frac{\left(\frac{\pi}{180}\right)\omega_{s'} sin\delta \sin(\emptyset - \beta) + cos\delta \cos(\emptyset - \beta)\, sin\omega_{s'}}{\left(\frac{\pi}{180}\right)\omega_s * sin\delta sin\emptyset + cos\delta cos\emptyset sin\omega}$$

ω'_s is the sunset hour angle for an inclined surface (in degrees) and is given by

$$\omega'_s = \min\{\omega_s, cos^{-1}[-tan\delta\tan(\emptyset - \beta)]\}$$

R_b is the beam radiation factor and ρ_g is ground reflectivity, (i.e. 0.2 for ordinary ground)

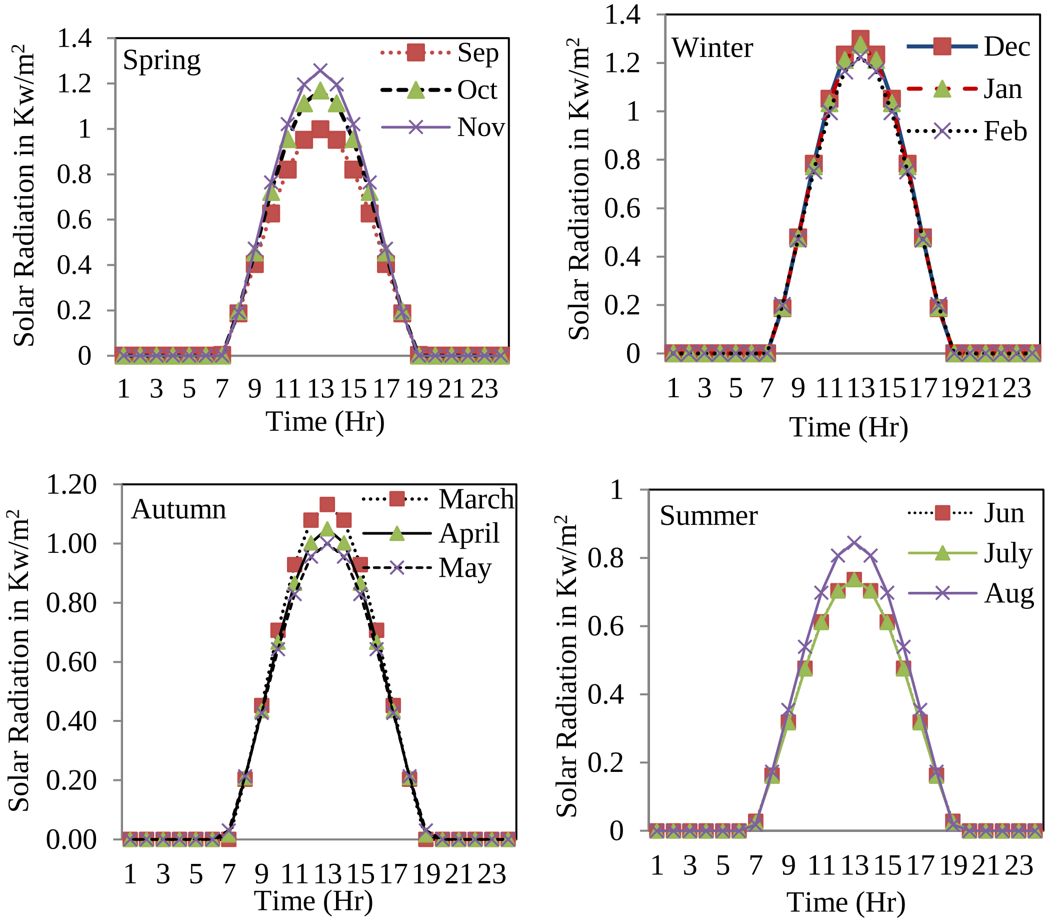


Figure 3.7 Monthly average hourly global radiation over the inclined surface at **25**° in kw/m^2

The above figures show that the solar energy potential of Adama city. The Monthly Average Total Solar radiation on Solar collector surface (H_t) is estimated as 29MJ/m^2/day and Monthly average hourly global radiation over the inclined surface in kw/m2 is estimated as 675Watts/m^2 as shown in Figure 3.16.

This section also defines the working principles and methods of controlling the main parameters affecting the system operations are.

3.3. Determination of system load, Sizing the system components

The solar thermal-powered egg incubator with a solar collector and a heat storage unit has been studied in this work. The system has been shown schematically in Figure 3.5. The system consists of an eggs chamber, a solar collector, and a heat storage unit. The eggs chamber has been designed to maintaining a suitable temperature for egg incubation.

The solar collector is designed to convert solar radiation into heat (thermal) energy. It has a glass cover on the top, a solar absorber, air space, and an insulator at the bottom. It has an inclination angle of 25^{o} facing to the south direction. The paraffin wax has been used as thermal energy storage for the nighttime. The following methodologies are taken out for designing the system:

- ✧ Calculating and predicting the system energy load
- ✧ Designing of the solar air heater for the system
- ✧ Designing thermal energy storage for the system and simulating models of PCM storage and
- ✧ Simulating the charging effects of solar thermal energy storage with ANSY fluent 16.2.
- ✧ Experimentally evaluating the performance of the whole system components

3.3.1. Design Analysis of the System Components and Energy System

3.3.1.1. The Design Criteria

The design of an egg incubator is dependent up on four parameters. These are eggs chamber Temperature, humidity, ventilation, and egg turning. It is designed to maintain them for the development of eggs embryo to fully developed chick. The following criteria are to be considered for successful egg incubator operation.

The system has to be designed to:

- ✓ Maintaining the temperature of the eggs chamber in between $35 - 39$℃ for 24 hours
- ✓ Maintaining the relative humidity of the incubator chamber in between 50-70% during the eggs incubation period
- ✓ Regularly turning the eggs inside the system at least three times a day
- ✓ Ventilating the system throughout the process

3.3.1.2. Incubator Design

A double-walled conventional heating unit with an outer body of wood, the inner chamber is made up of foam and covered with thin aluminum foil (to reduce heat loss). Also, manually adjustable egg tray turning is designed. Wood and foam are have low thermal conductivity and insures maximum thermal efficiency inside the chamber.

3.3.1.3. Egg Tray

The three eggs trays were designed for the system and each has the capacity of carrying 70 eggs. The size of the egg trays was depend on the number of eggs on the trays.

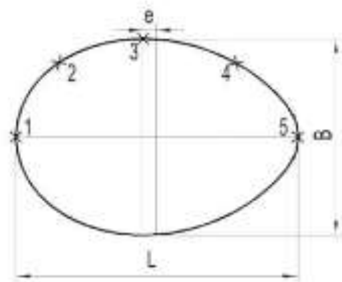


Figure 3.8: Major and minor diameter of an egg (Geometric size of chicken eggs) (http://www.scielo.br/scielo.php?pid=S1516-635X2017000300455&script=sciarttext)

The capacity of the incubator eggs trays:

The eggs have major and minor diameters. Based on the major and minor diameter of eggs the size of eggs trays will be determined. The eggs sizes are described as the following:

Major diameter of an egg (L) = 60mm

Minor diameter of an egg (B) = 46mm

The volume of the egg tray can be estimated as: $Vegg = \frac{\pi B^2 * L}{4} * n;$

The length and width of the egg tray will be:

$$L_{et} = 10mm + 10 * B$$

$$L_{et} = 10mm + 10 * 46mm = 470mm$$

$$W_{et} = 110mm + 7 * L$$

$$W_{et} = 110mm + 7 * 46mm = 432 \approx 450mm$$

The size of the eggs chamber is determined by the size of the eggs trays. Therefore, the inside volume of the chamber 1mx1mx1m is enough for including the space taken by the thermal storage unit built in it.

3.3.1.4. Eggs turning

Eggs turning is performed at least three times a day by using the moveable egg tray designed in the system manually. This keeps the embryo centered in the egg and prevents it from sticking to the shell membrane. The eggs turning were stopped at the last three (3) days of the incubation cycle (at 18 days for chickens) [**60]**.

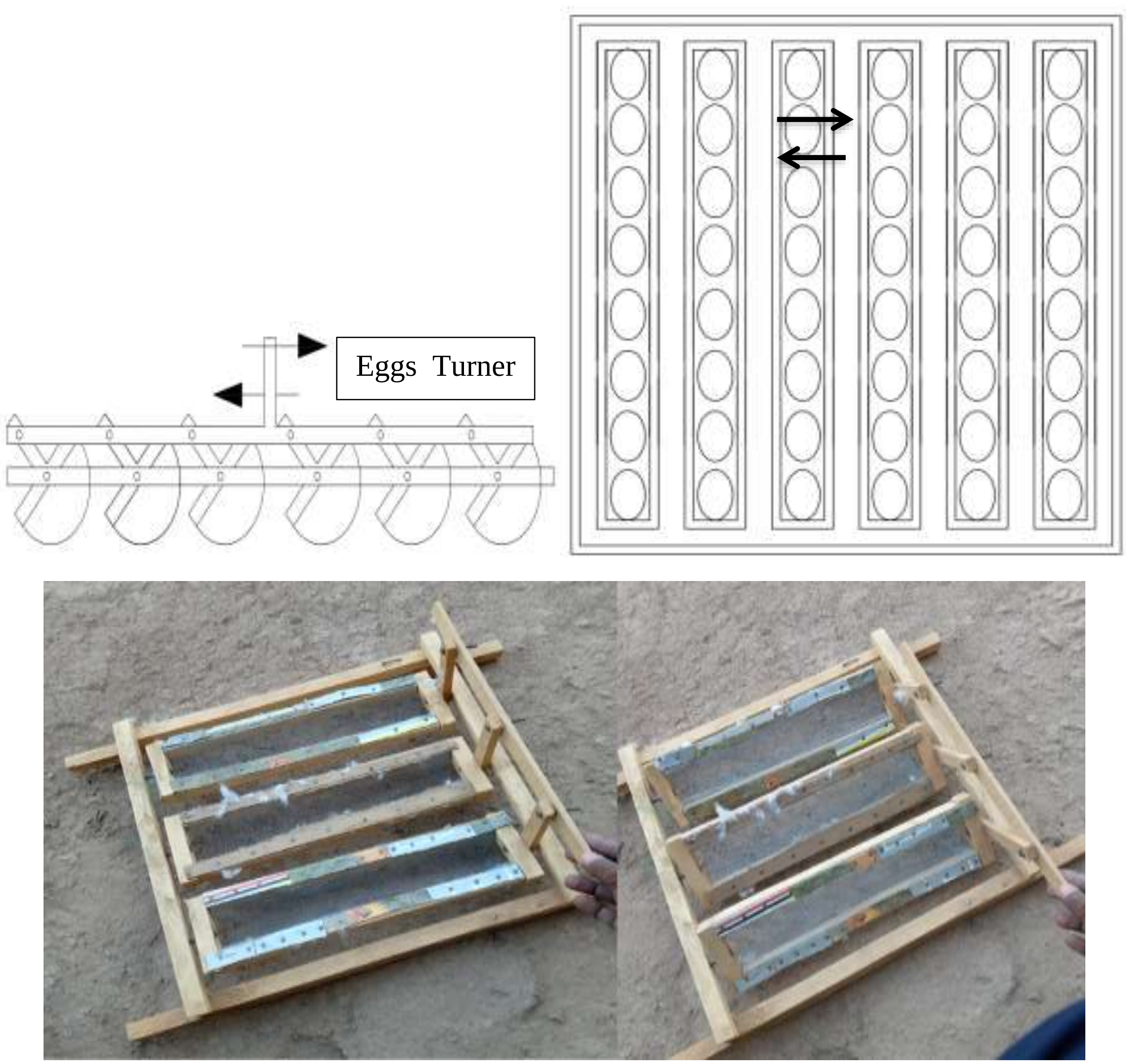


Figure 3.9 The eggs trays and turners

3.3.2. Thermal Analysis of the System (an Egg Incubator)

The system energy model has been derived to describe heat transfer characteristics of the eggs incubator by presenting the relationship between input and output energy through and energy stored inside the eggs in the chamber. In this section, the energy analysis of solar thermal powered chicken egg incubator has been specifically for hatching chicken eggs, which will hold about 200 eggs.

According to the conservation of energy:

$$\text{The rate energy stored into the system} = \text{The rate energy entering into the system} + \text{The rate energy leaving the system}$$

$$\frac{d[\rho c V T_c]}{dt} = \dot{E}_{in} - \dot{E}_{out} \quad \text{(3.15)}$$

A mathematical model has been derived to describe the heat transfer characteristics of the eggs chamber (incubator).

$$\dot{Q}_{egg} = \dot{Q}in - (\dot{Q}_L + \dot{Q}_{vent}) \quad \text{(3.16)}$$

The rate of energy required raises the temperature of the egg from ambient temperature to 39℃

$$\dot{Q}_{egg} = n * m_{egg} C_{egg} \frac{\Delta T}{\Delta t} \quad \text{(3.17)}$$

Where, $\dot{Q}_{egg}$ is the rate of energy required to raise the temperature of the egg from ambient temperature to 39℃, n is number of eggs inside chamber and m_{egg} is a mass of eggs (kg)

The ΔT per minute and the K value showed no significant difference between the large broiler breeder and turkey eggs. [45] Describes the specific heat (C_p) for whole eggs has been (3.23 kJ /kg*K), $m_{egg} = 65g = 0.065kg$ *and* n = 200eggs.

Table 3.3. Properties of eggs (Renema *et al*, 2006)

Egg Type	Egg weight (g)	Temperature Change (°C $* min^{-1}$)	Time to Ambient Temperature $(t_{amb})(min)$	Specific Heat of Egg
Small Broiler Breeder	54.22	0.204	210	3.23kJ/kg*K
Large Broiler Breeder	66.05	0.195	213	
Turkey	87.74	0.190	218	
SEM	0.56	0.0027	5	

Assumptions:

- ✓ This energy amount is to be determined from the load, which should be accomplished by the system.
- ✓ During the process, the temperature of the eggs inside the chamber needs to be heated from $20\ to\ 39$°C.
- ✓ The energy lost through the chamber wall and ventilation is to be considered.
- ✓ The specific heat of the eggs (C_{peggs}) is 3.23kj/kg $*$ °C with an average mass of 65gs (0.065kg).

The amount of energy use to raise 200eggs temperature from 20 to 39°C is:

$$Q_{egg} = n * m_{egg} * \Delta T \ = 839.8 \text{ kJ}$$

The rate at which the egg temperature change has been given as Table B.2.; and the rate of energy required to raise the temperature of the eggs from room to incubation temperature has been calculated as:

$$\dot{Q}_{\text{egg}} = n * m_{egg} * \frac{\Delta T}{\Delta t} = 142.766\text{watts}$$

3.3.2.1. Heat loss through the eggs chamber walls

The heat leaving the egg chamber through the walls:

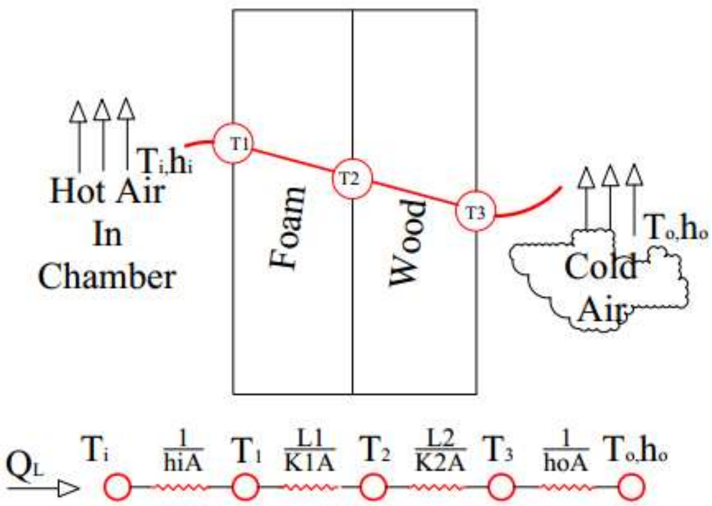


Figure 3.10. Thermal networks of the eggs chamber walls

Thus, the heat loss through the walls will be: $\dot{Q}_L = \frac{\Delta T}{R_{tot}} * 5$

The thermal network of chamber walls has been shown in Figure 4.1. The overall thermal resistance between the wall and the chamber is: $R_{tot} = \frac{1}{h_i A} + \frac{L_1}{K_1 A} + \frac{L_2}{K_2 A} + \frac{1}{h_o A}$

Where: A is the area of the chamber wall ($0.5m^2$)

$$R_{tot} = (\frac{1}{4w/K} + \frac{0.04}{0.045 * 0.5w/K} + \frac{0.02}{0.17 * 0.5w/K} + \frac{1}{10w/K}) = 2.48K/watts$$

Thus, the total heat loss through the walls will be:

$$\dot{Q}_L = \frac{\Delta T}{R_{tot}} * 5 = (20K/2.48K/watts) * 5 = 40.32watts.$$

3.3.2.2. The Heat Loss through Ventilation

Natural ventilation, as the name implies, is a system using natural forces to supply the egg chamber with fresh and hot air. Air exchange is accomplished through designed inlets and outlets in the chamber. Thus, most of the relationships in natural convection are based on Rayleigh experimental correlations. The Rayleigh number is defined as the product of the Grash of and Prandtl numbers: **[72]**

$$Ra_h = Gr * Pr = \frac{g * \beta(T_s - T_\infty)}{v * \alpha} * H^3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.18)$$

The Nusselt number in natural convection is in the following form:

$$Nu = \frac{h*L}{k} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.19)$$

For a vertical plate, the characteristic length is L.

$$Nu = \begin{cases} 0.59Ra^{1/4}, & 10^4 < Ra < 10^9 \\ 0.1Ra^{1/3}, & 10^9 < Ra < 10^{13} \end{cases}$$

Note that for ideal gases, $\beta = 1/T_\infty$ where T_∞ is the ambient air temperature

$$Ra_h = Gr * Pr = \frac{g * \beta(T_s - T_\infty)}{v * \alpha} * L^3$$

$$\dot{Q}_{vent} = \dot{V}_{fa} * \rho_a * Cp_{air} * \Delta T \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.20)$$

Natural convection correlations the complexities of the fluid flow make it very difficult to obtain simple analytical relations for natural convection Rayleigh correlations. By using Eq. 26 & 27 the load consumed by the ventilation system has been estimated as follows: The properties of the air at $T_f = \frac{T_a+T_{in}}{2} = \frac{300K+312K}{2} = 306K$: $C_{pa} = 1.0055kJ/\,kg * ℃, \rho_a = 1.1774kg/m^3, \mu_a = 1.983kg/m.s, v = 15.68 * 10^{-6}m^2/sec, \alpha = 0.22160 * 10^{-4}m^2/\sec^2$, $Pr = 0.708$

$$\beta = \frac{1}{313K} = 0.03205/K$$

$$R_a = \frac{\left(\frac{9.81m}{s^2}\right) * (3.205 * 10^{-3}) * (40 - 20)}{(15.68 * 10^{-6}m^2/\sec) * (0.22160 * 10^{-4}m^2/\sec^2)} * (0.5m)^3 = 2.26 * 10^8$$

$$Nu = \frac{h * L}{k} = 0.59 * (2.26 * 10^8)^{\frac{1}{4}} = 72.34$$

$\frac{h*0.5m}{\frac{0.02624W}{m*K}} = 72.34$; $h_{air} = 3.80Watts/(m^2 * K)$

The ventilation will be done 24 hours a day. Thus, the system ventilation hole is also calculated as:

$$Q_{vent} = A_{hole} * h_{air} * \Delta T = \dot{V}_{fa} * \rho_a * Cp_{air} * \Delta T$$

$$A_{hole} = 0.0075m2 \rightarrow d_{hole} = \sqrt{\left(4 * \frac{A_{hole}}{\pi}\right)} = 9.56 * 10 - 3m \approx 0.01m = 10mm = 1cm$$

The required ventilation energy of the incubator is calculated as:

$$\dot{Q}_{vent} = \dot{V}_{fa} * \rho_a * Cp_{air} * \Delta T$$

$$\dot{Q}_{vent} = 0.57\text{watts}$$

$$Q_{Vent} = 0.57\text{watts} * 24\text{hr} * \frac{3600\text{sec}}{1\text{hr} * 1000} = 49.25\text{kJ}$$

The energy has been continuously lost through the chamber wall for at least 16hr per day (during no sunshine). Therefore, the energy lost per day from the egg chamber through the chamber wall will be:

$$Q_L = 40.32\text{J/sec} * \frac{16\text{hr}}{\text{Day}} * \frac{3600\text{sec}}{1\text{hr}} = 2{,}322{,}432\text{J/Day} = 2.32\text{MJ/Day}$$

The total energy required for the system has been calculated by summation energy consumed by eggs heating, the energy lost through ventilation and walls.

$$Q_t = Q_{egg} + Q_{vent} + Q_L$$

$$Q_t = 3.21\text{MJ}$$

Lets consider the 50% extra loss of total energy; the total amount of thermal energy required for the system has been estimated as:

$$Q_T = 1.5Q_t$$

$$Q_T = 4.82\text{MJ}$$

For this work, the following criteria are used for selection of thermal energy storage material for the system based on the literatures reviews.

The rate of energy for heating the whole system to incubation temperature has been:

$$\dot{Q}_{in} = \dot{Q}_{egg} + \dot{Q}_L + \dot{Q}_{vent} = 142.766\text{watts} + 40.32watts + 0.57watts$$

$$Qin = 183.656\text{watts}$$

The time taken for heating the eggs to the incubation temperature has been:

$$\frac{Q_{egg}}{\Delta t} = \dot{Q}_{egg}$$

$$\frac{840000\text{J}}{\Delta t} = 183.656\text{J/sec}, \Delta t = 4{,}573.77\text{sec} \approx 1\text{hr and } 30\text{minute}$$

The egg chamber has been first charged with the power of 183.66watts for one and half hours (1hr and 30minute) until the egg temperature reaches incubation temperature.

3.3.3. Design of LTES for the System

3.3.3.1. The Criteria for Selection of Latent Heat Storage

EL HAYEK et *al* (2013) illustrate that latent heat storage can store a high energy density. It is easily noticed that latent heat is larger than sensible heat (for a slight temperature difference) and that the melting points depend on the user's body. This criterion allows the use of a wide range of Phase Change Materials (PCM) according to the desired temperatures. Due to its main advantages, latent heat storage is the preferred space heating application. Works of literature describe the selection criteria of phase change material as follows:

- **Melting point:** Phase change materials should have a melting point near the required operating temperature range of the TES system. Paraffin wax has a suitable melting temperature that is closed to the required operating temperature of the system.
- **Density:** High density improves energy storage density which reduces the volume of the TES system.
- **Latent heat of fusion:** Phase change materials should have a very high latent heat of fusion. High latent heat of fusion improves the energy storage density of the system.
- **Specific heat (Cp):** Sensible heat storage materials should have high specific heat. High specific heat improves the energy storage density of the system.
- **Cost and availability:** The cheaper price of storage material reduces capital and operational costs. They should be abundantly available. Paraffin wax has been cheap, commercially abundant, and available phase change material on the market, **[16]**.

Table 4.1 Thermophysical properties of some paraffin wax (Fathi, 2020)

S/N	Type	S. Heat [kJ/kg*K]	M. Temp [°C]	Latent heat (kJ/kg)	Density (kg/m^3)
1	C16-C28	2000	42 - 44°C	189	910
2	C20-C33	2000	48 - 50°C	189	912
3	C22-C45	2000	58 - 60°C	189	920

The selection of suitable phase change materials should have a melting point near the required operating temperature range of the TES system.

3.3.3.2. Design of Thermal Energy Storage for the System

The size of thermal energy storage was designed based on the energy demands of the system. The maximum required temperature of an egg incubator for successfully hatching chicken eggs is 39℃. Hence the temperature of the chamber is comfortable in between 35 to 39℃. The initial temperature of eggs is assumed to be 20℃ and desired eggs temperature is 39℃. Paraffin wax has a suitable melting temperature that is closed to the required operating temperature of the system. Therefore paraffin wax with a transition temperature between 42 to 44℃ is suitable for the system operation. These types are paraffin wax is very stable and does not affect the system operation.

The storage capacity of the LHS system with a PCM medium (paraffin wax) is given by:

$$Q_{stored} = \int_{Ti}^{Tm} mC_p dT + m\Delta h_m + \int_{T_m}^{T_f} mC_p dT \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (3.21)$$

The stored thermal energy in the thermal storage medium is assumed to be equal to the total energy required for keeping the egg's chamber and incubation temperature constant.

Therefore: $\mathrm{Q_T = Q_{stored} = m_{pcm} * (Cp * \Delta T} + \Delta hm)$

$$4{,}820000\mathrm{J} = \mathrm{m_{pw}}((2000\mathrm{J/kg} * \mathrm{K}) * (23\mathrm{K}) + 189{,}000\mathrm{J/kg}) = m_{pw} * 280000\mathrm{J/kg}$$

$$m_{pw} = \frac{4{,}820000\mathrm{J}}{280000\mathrm{J/kg}} \approx 20kg$$

The volume of thermal storage material will be calculated as the following:

$$\rho = \frac{mass\ of\ mater}{Volume\ of\ mater} \rightarrow Volume\ of\ mater = \rho * mass\ of\ mater$$

The density of paraffin wax is 910kg/m3 as described in Table 4.1.

$$V_{TES} = \frac{m_{pw}}{\rho_{TES}} = \frac{20kg}{910kg/m^3} = 0.0219780m^3$$

To increase the heat transfer between heat transferring fluid and thermal energy storage unit the energy storage material must be divided into compartments. In this work let divide the thermal energy storage unit into 5 compartments.

$$Vunit = \frac{Vpw}{5} = \frac{0.0219780m^3}{5} = 0.0044m^3$$

Therefore fabricated prototype contains the paraffin wax for latent heat storage and it has been made of 5 rectangular containers filled with paraffin wax of length 350cm, height 250cm, and width of 0.25cm. Each container can maintain 3kg of paraffin wax.

The temperature has been the main factor affecting the incubation of the eggs. The literature describes the required egg chamber temperature for incubator operation as in the range of $35 - 39°C$. The egg's chamber temperature has been controlled by using of OMRON thermocouple installed inside the chamber. The thermocouple switches on/off the fans inside the chamber for keeping the chamber temperature constant (incubation temperature). When the temperature inside the eggs chamber is above the incubation temperature the thermostat switch on the ventilating fan for cooling the chamber up to the required range for the system and vice versa.

3.3.4. Solar Collector Energy Output and Determination of Area

3.3.4.1. Energy Gained by the Solar Collector

The general energy balance of the collector is given by [**72**]

$$\left[\frac{\text{Accumulation of total energy}}{\text{time}}\right] = \left[\frac{\text{The input of total energy}}{\text{time}}\right] + \left[\frac{\text{The output of total energy}}{\text{time}}\right] \ldots\ldots (3.22)$$

The heat absorbed by the heat transfer fluid as it passes through the collector is equal to the heat gains of the collector minus the heat loss from it. The solar energy $\dot{Q}$, absorbed by the absorber plate of the collector can be calculated as

$$\dot{Q}_s = IA_c\tau\alpha \ldots\ldots (3.23)$$

Both τ and α are dimensionless and depend on the incidence angle of the collector, both decrease as the incidence angle increases.

The heat loss of the collector Q is given by [**72**]

$$\dot{Q}_l = U_tA_c\left(T_{pm} - T_a\right) \ldots\ldots (3.24)$$

The heat exchange between the collector and its surroundings may occur from upper and lower surfaces and the sides. The heat absorbed by the fluid $\dot{Q}_f$ as it passes through the collector can be calculated as:

$$\dot{Q}_f = \dot{m}c(T_a - T_o) \ldots\ldots (3.25)$$

For simplicity, it is assumed that the liquid in the solar collector is completely mixed. Then, the energy balance of the collector based on Eqs. 15, 16, 17 & 18 can be given by: **[72]**

$$\frac{d[\rho cVT_c]}{dt} = IA_c\tau\alpha + UA_c\left(T_{pm} - T_a\right) + \dot{V}_C\rho c_{in}T_{in} - \dot{V}_c\rho_{out}c_{out}T_c \ldots\ldots\ldots\ldots\ldots\ldots (3.26)$$

Where $\dot{m} = \dot{V}_c\rho_{in} = \dot{V}_c\rho_{out}$ and V is the volume of fluid passage in the collector.

The following assumptions are kept:

1. $\rho\ in = \rho out = \rho$
2. $C, in = Cout = C,$
3. $V\ is\ constant.$

Taking into consideration the assumptions Eq. (4.11) can be rewritten as **[72]**

$$\frac{d[\rho cVT_c]}{dt} = IA_c\tau\alpha + UA_c(T_P - Ta) + \dot{m}c(T_{in} - T_c) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.27)$$

The outlet temperature of the air in terms of F_R is:

$$T_{out} = T_{in} + F_R * \frac{[I(\tau\alpha) - U_L(Tpm - Tair)]}{\dot{m}C_p} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.28)$$

The useful energy gain is expressed in terms of inlet air temperature T_{in} and other system and operating parameters as **[72]**

$$F_R = \frac{\dot{m}C_p}{A_pU_l}\left[1 - \exp\left(\frac{F'U_lA_p}{\dot{m}C_p}\right)\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.29)$$

Collector efficiency factor (F') is expressed as:

$$F' = \frac{1}{\left(1 + \frac{U_l}{h_e}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.30)$$

$$Q_a = A_c[IR(\tau\alpha)] = Q_u + Q_l \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.31)$$

3.3.4.2. Collector Overall Heat Loss Coefficient

The absorbed energy S is distributed to thermal losses through the top and bottom and to useful energy gain.

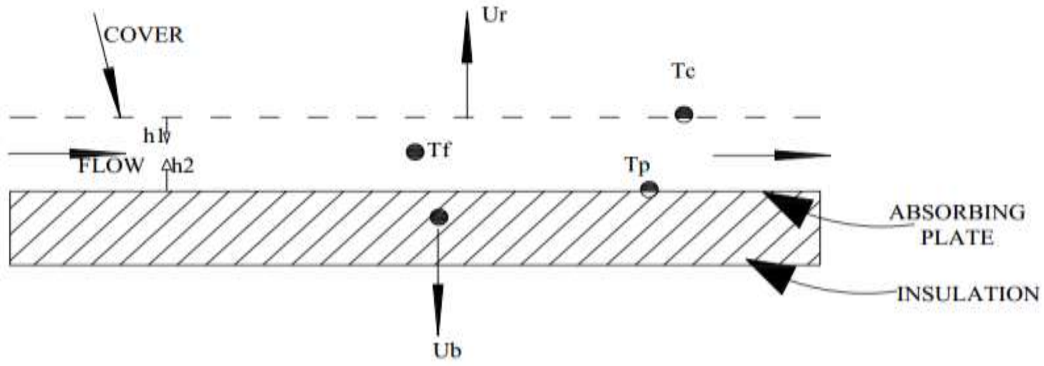


Figure 3.11 Schematic diagram of solar air heater

The energy loss through the top is the result of convection and radiation between parallel plates. The loss through the top per-unit area is then equal to the heat transfer from the absorber plate to the first cover: **[72]**

$$q_{loss,top} = h_{c,pc1}(T_p - T_{c1}) + \frac{\sigma({T_p}^4 - {T_{c1}}^4)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_{c1}} - 1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.32)$$

Where: $h_{c,pc}$ is the convection heat transfer coefficient between two inclined parallel plates.

The plate efficiency factor F' is **[72]**

$$F' = \left[1 + \frac{UL}{(h + \left[\left(\frac{1}{h}\right) + \left(\frac{1}{hr}\right)\right]^{-1}}\right]^{-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.33)$$

The collector heat removal factor is the product of the plate efficiency factor F' and the collector flow factor F''

$$\mathrm{F''} = \frac{\mathrm{FR}}{\mathrm{F'}} = \frac{\dot{\mathrm{m}}\mathrm{Cp}}{\mathrm{A_c U_L F'}}\left[1 - \exp\left(-\frac{\mathrm{AcULF'}}{\mathrm{mCp}}\right)\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.34)$$

$$\mathrm{F_R} = \frac{\dot{\mathrm{m}}\mathrm{Cp}}{\mathrm{A_c U_L}}\left[1 - \exp\left(-\frac{\mathrm{AcU_L F'}}{\mathrm{mCp}}\right)\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.35)$$

$$F_R = F' * F'' \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.36)$$

The collector heat removal factor times this maximum possible useful energy gain is equal to the actual useful energy gain Q_u: **[72]**

$$Q_u = A_c * F_R[S - U_t(T_{pm} - T_a)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.37)$$

3.3.4.3. Collector thermal efficiency

The efficiency of a solar collector is defined as the ratio of the amount of useful heat collected to the total amount of solar radiation striking the collector surface during any period: **[72], [46]**

$$ή = \frac{Q_u}{I_o * A_c} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (3.37)$$

The equation for mass flow rate ($\dot{m}$) is

$$\dot{m} = \rho * \dot{Q} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (3.38)$$

Where: ρ is the density of air, which depends on the air temperature and

$\dot{Q}$ is the volume flow rate, which depends on the pressure difference at the orifice as measured from the inclined tube manometer and temperature

Useful heat collected for an air-type solar collector can be expressed as:

$$Q_u = \dot{m}C_p(T_{out} - T_{in}) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (3.39)$$

Therefore, the collector thermal efficiency becomes,

$$ή = \dot{m}C_p \frac{(T_{out} - T_{in})}{I_o * A_c} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (3.40)$$

The overall rate of heat lost per square area from the absorber to the ambient air through the glass cover and bottom insulation is given by:

$$\dot{q}_L = U_L(T_p - T_a)$$

Where $\dot{q}L$ is the overall heat lost from the absorber to the ambient air. To calculate the overall top loss heat transfer coefficient from the absorber to ambient through the glass cover of an FPC for the following specifications.

3.3.4.4. Determination of Area

By assuming the mean glass temperature (Tg) = 40℃, the radiative heat-transfer coefficient from the absorber plate to the cover, Eq. (20), can be calculated as:

$$h_{lr} = \frac{0.84 * 5.6697 * 10^{-8}((60 + 273.15)^4 - (40 + 273.15)^4)}{60 - 40}$$

$$h_{lr} = 6.426 W/m^2 * ℃$$

The radiative heat-transfer coefficient from glass cover to the sky, Eq. (3.32), can be calculated as:

$$h_{lr} = \frac{0.84 * 5.6697 * 10^{-8}((40 + 273.15)^4 - (20 + 273.15)^4)}{40 - 20}$$

$$h_{lr} = 7.02 W/m^2 * ℃$$

The average air temperature in the space between the glass and the plate is 50°C. The physical properties of air at this temperature are as follows:

$$\vartheta = \frac{1.96x10^{-5}m^2}{sec}, K = 0.0293 w/m^2 * ℃, g = \frac{9.81m}{s^2}, T = 340.5K, \mathrm{Pr} = 0.7$$

Then the Rayleigh number (Eq.21) can calculate as follows:

$$\mathrm{Nu} = 0.145((\mathrm{Gr_L} * \mathrm{Pr})^{1/3} - ((\mathrm{Gr_C} * \mathrm{Pr})^{1/3})) + 0.56(\mathrm{Gr_C} * \mathrm{PrCos\theta})^{1/4}$$

$$\mathrm{Nu} = 0.145((11.134 * 10^6 * 0.7)^{1/3} - ((1.391 * 10^6 * 0.7)^{1/3})) + 0.56(1.391 * 10^6 * 0.7 * \mathrm{Cos}25)^{1/4}$$

$$\mathrm{Nu} = 129.80$$

The convective heat transfer coefficient has been calculated as follows:

$$h_{lc} = Nu * \frac{K}{L} = 129.80 * \frac{0.0293}{0.025}(W/m^2 * °C) = 152.12 W/m^2 °C$$

The value of the top loss coefficient (Ut) is computed by using the equation proposed by **Klein (1975)**

$$U_t^{-1} = \left[\sigma(Tp^2 + Tg^2)(Tp - Tg) + \left(\frac{Ka * Nu}{Lg}\right)\right]^{-1} + [\sigma\varepsilon_g(Tp^2 + Tg^2)(Tp - Tg) + h_W]^{-1} + \frac{t_g}{K_g}$$

$$U_t^{-1} = \left[(5.567 * 10^{-8})((343.15K)^2 + (313.15K)^2)(343.15K - 313.15K) + \left(\frac{(0.025W/m * K) * (23.42)}{0.005m}\right)\right]^{-1} + ((5.567 * 10^{-8}) * (0.85) * ((343.15K)^2 + (313.15K)^2)(343.15K - 313.15K) + 10)^{-1} + \frac{0.005m}{0.78w/m * K}$$

$$= [0.3604 + 11.05]^{-1} + (10.306)^{-1} + 0.00641 = 0.19108(m^2 * K)/Watts$$

$$U_t = 5.2334 Watts/m^2 * K$$

The conductive heat-transfer coefficient of the glass cover (h_k) can also be calculated from Eq. (18), as:

$$h_k = \frac{0.78}{0.005} = 156 w/m^2 * ℃$$

Bottom lose coefficient from Eq. (20)

$$\mathrm{Ub} = \left[\frac{\mathrm{L_i}}{\mathrm{K_i}} + \frac{1}{\mathrm{h_b}}\right]^{-1}$$

$$\mathrm{Ub} = 3.75\mathrm{w/m^2} * ℃$$

Therefore, the overall heat transfer coefficient (W/m^2*°C) through the collector walls has been estimated as:

$$U_L = U_t + U_b$$

$$U_L = 9.08Watts/m^2 * ℃$$

The average overall rate of heat lost per area from the absorber to the ambient air

$$\mathrm{q_L} = \mathrm{U_L}(\mathrm{T_p} - \mathrm{T_a})$$

$$\mathrm{q_L} = 317.94\mathrm{watts/m^2}$$

The average heat lost per area through the solar collector wall during the sunshine hour will be calculated by multiplying the overall rate of heat lost from the solar collector with the average sunshine hour of Adama city, Ethiopia.

Therefore:

$$\dot{q}_L = (317.94\frac{J}{\mathrm{sec}} * \frac{7hr}{1Day} * \frac{3600sec}{1hr})$$

$$= 8012088\mathrm{J/m^2/Day}$$

The plate efficiency factor F' is

$$F' = \left[1 + \frac{9.084}{(152.12 + \left[\left(\frac{1}{152.12}\right) + \left(\frac{1}{6.426}\right)\right]^{-1}}\right]^{-1} = 0.94\ from\ (17)$$

Thus, the useful energy output of the solar collector is:

$$Q_u \ = \ A_c * F'\left[S - U_t\left(T_{pm} - T_a\right)\right] \ldots \ldots \ldots \ldots \ldots \ldots \ldots from\ eq(21)$$

$$\frac{Qu}{Ac} = F' * [S - qL]$$

$$q_u = F' * [H_b * \tau\alpha - q_L]$$

From Table B.4 the average solar radiation fall on the solar collector surface has been 29.52MJ/m2/Day.

$$qu = 0.33 * ((29520000J/m2/Day) * (0.75) - (8012088J/m2/Day))$$

$$= 4{,}662{,}210.96\mathrm{J/m2/day} \approx 4.66\mathrm{MJ/m^2/Day}$$

The total energy required for the system per day has been 4.82MJ/Day.

Table 4.2 Properties of materials used

Thermal conductivity	
Paraffin wax	0.24w/m*K
Air	0.024w/m*K
Foam	0.045w/m*K
Wood	0.17w/m*K

The effective heat collecting area of the solar collector can be assumed as:

$$A_e = \frac{Qt}{qu} = \frac{\frac{4.82MJ}{day}}{\frac{4.66MJ/m^2}{day}} = 1.18m^2 \leftrightarrow say\ 1.5m^2$$

$$\mathrm{F_R} = \frac{(0.00773086\mathrm{kg/sec})(\frac{1005\mathrm{J}}{\mathrm{kg*K}})}{9.084\mathrm{W/K} * 2\mathrm{m^2}}\left[1 - \exp\left(-\frac{\frac{9.084\mathrm{W}}{\mathrm{m^2}} * \mathrm{K} * 2\mathrm{m^2} * 0.94}{(0.00773086\mathrm{kg/sec})(\frac{1005\mathrm{J}}{\mathrm{kg*K}})}\right)\right] from\ equation\ (19)$$

$$\mathrm{F_R} = 0.38$$

The collector heat removal factor times this maximum possible useful energy gain is equal to the actual useful energy gain Q_u:

$$Q_u = 2m^2 * 0.38 * \left[\frac{1065.97\mathrm{watts}}{\mathrm{m^2}} * 0.74 - \frac{317.94\mathrm{watts}}{\mathrm{m^2}}\right]$$

$$\mathrm{Qu} = 357.87\mathrm{Watts}$$

By assuming the change of the inlet and outlet temperature of the air of solar air heater 40℃ it can be possible to calculate the maximum possible air mass flow rate.

Therefore:

$$Qu = 357.87\text{Watts} = \dot{m}Cp\Delta T = \dot{m} * 1005J/kg * K * 40K$$

$$\dot{m} = \frac{357.87\text{Watts}}{1005 * 40J/kg} = 0.008902kg/sec$$

An average outlet temperature of a solar air heater in terms of F_R is estimated as the following:

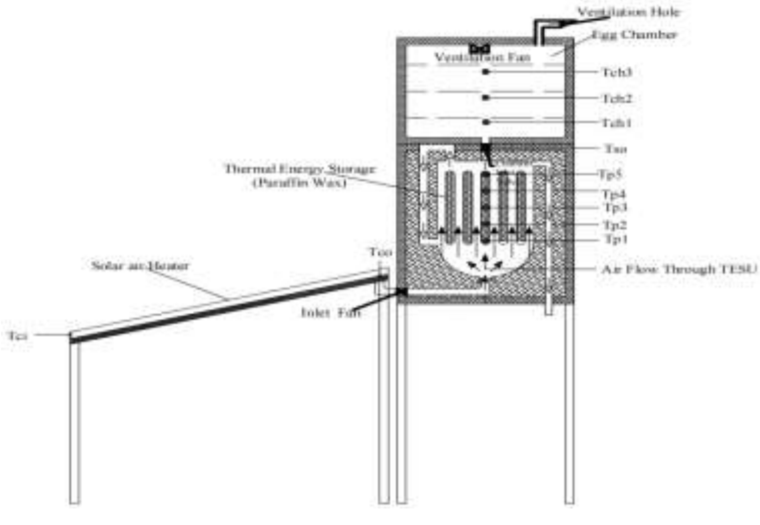
$$T_{out} = 20 + 0.38 * \frac{[(1065.97\text{watts/m}^2 * 2\text{m}^2) * (0.75) - (317.94watts/m^2 * 2m^2)]}{0.008902kg/sec * 1005J/kg * K} \; from(9)$$

$$T_{out} = 20℃ + 43.63℃ = 63.63℃$$

The temperature of HTF has been at an average of 63.5℃. The energy storage capacity of the thermal storage medium has been assumed as follows:

3.3.5. Working Principles of the System

The source of the heat for the system is solar thermal energy. The flat plate collector is used to convert solar radiation into thermal energy for the system. The air is used as heat transferring fluid. Heated air by the collector intern heats thermal energy storage of the system for use during the night time and also for heating the eggs chamber.



The System Description

1. T_{ch} Chamber Temperature on tray 1,2,&3
2. T_p The Paraffin wax Temperature
3. Tci Air temperature at the inlet of Solar air collector
4. T_{co} Air temperature at the outlet of solar air collector
5. Tso air temperature from TESU

Figure 3.12 Schematic Diagram of Solar Thermal Incubator

Chamber temperature must be maintained in the range of 35 to 39℃. To control the temperature inside the system the OMRON thermocouple has been used. It acts as a switch for the ventilating fan, whenever the chamber temperature becomes above 39℃. Pan of water is also placed under the eggs trays for humidifying the system.

3.3.5.1. Controlling Humidity:

In the incubators, humidity is attained by filling a pan or some other reservoir in the incubator with water. The egg incubator is needed to be maintained at a temperature of 37.75℃ and 65% relative humidity. The ambient air temperature and the average relative of Adama Town are 20℃ and 54.6% respectively. The heating load of the system is assumed to be 45watts. For most eggs, relative humidity of between 55 and 60 percent is adequate during the early period of incubation. During the last 3 to 4 days just before hatching, humidity should be increased to about 70 percent.

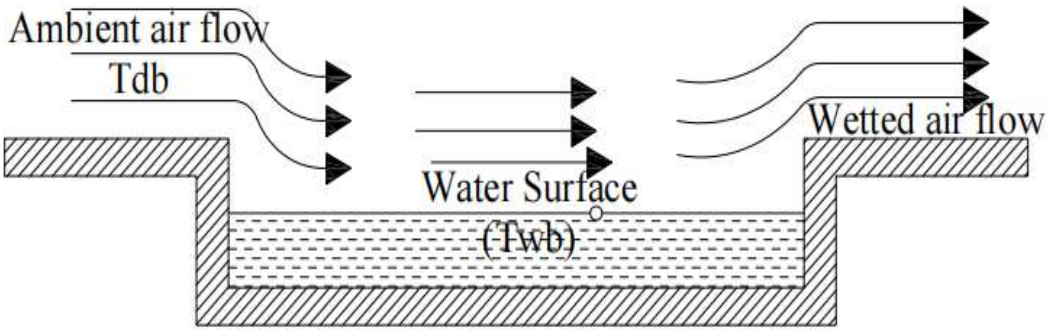


Figure 3.13 the pan carrying water for humidifying the chamber

The relative humidity has been obtained from wet and dry bulb temperatures measure with thermocouples' wires of the wet surface. The system relative humidity has been determined by using dry bulb temperature and wet bulb temperature from the Psychrometric chart as shown in Figure 3.7.

3.4. Materials

The whole components of the system were designed and constructed by using locally available material. It consists solar air heater, thermal storage unit, and eggs chamber. The solar air heater has been consisting of a glazing cover on the top, air space in the middle, absorber plate, and thermal insulation. The atmospheric air is used as heat transferring fluid (HTF).

Figure 3.13 Solar Thermal incubators System and its Components

The thermal energy storage system has been designed and constructed independently inside the incubator chamber and below the eggs chamber of the system. The paraffin wax has been used as PCM (storage medium). The thermal energy storage system consists of five thermal energy storage units inside the 25mmx250mmx350mm steel containers each. The containers are used for carrying paraffin wax and hence enhance the heat transfer rate between the PCM (paraffin) and HTF.

Figure 3.14 Preparing of thermal storage units

The paraffin wax has been encapsulated inside five rectangular containers. The Thermo couples' wires were inserted into them for measuring the charging and discharging rate of the thermal storage unit.

3.4.1. Solar Air Heater

A flat plate solar air collector is used in the experiment as the source of thermal energy for the system. An expanded wire mesh is introduced on the absorber plate for roughening the absorber plate surface and hence enhances the rate of heat transfer in between the HTF (air) and absorber plate in the daytime.

Figure 3.15 Solar Collector and Expanded Wire mesh

Table 3.1 shows that the properties and specifications of the materials used to construct the system solar collector

Components	Size	Components	Size
Back-insulation thickness (Wood)	25mm	Insulation conductivity (Wood)	0.045W/m*K
Ambient temperature	20℃	Gross Collector length	1.5 m
Mean plate temperature	100℃	Gross Collector width	1 m
Collector sloped angel	25°	Edge insulation thickness (Wood)	25 mm
Collector thickness	250 mm	Absorber -plate emittance e_p	0.95
Absorber to glass cover spacing (L)	210mm	Expanded Wire mesh	1m x 1m
Glass-cover emmittance (ε_g)	0.88	Absorber plate (Stainless steel)	1m x 1m

3.4.2. Thermal Storage Materials

In this work, the phase change material (paraffin wax) has been used as a TES medium. The storage capacity of the paraffin wax has been assumed to be equal to the phase change enthalpy at the phase change temperature and sensible heat stored over the whole temperature range of the storage. Paraffin waxes and other pure paraffin have stable properties and good thermal reliability. Paraffin waxes are safe. Since they do not promote corrosion, they are compatible with metal containers [**16]**. For the work, the paraffin wax has been used as thermal energy storage to store 4MJ of thermal energy. The commercial 25kg of paraffin wax (PW) has been purchased from Wehib chemicals, Addis Ababa.

Figure 3.16 The slab of Paraffin Wax Purchased

The thermal properties of thermal storage were with a density of $910kg/m^3$, a heat capacity of $2kJ/kg * K$ and conductivity of $0.24W * m^{-1} * K^{-1}$. The paraffin wax properties were assumed to be constant throughout the melting and solidification processes. The storage medium is heated with the hot air of 63.6℃ from bottom to up and discharged with atmospheric air at a temperature of 20℃. The thermal storage unit consists of paraffin wax. The total mass of the paraffin wax used for the system has been $m_{PW} = 15kg$. The thermal storage has been charged during the sun is shining (t_c) and discharged to provide power during the night for the system.

3.4.3. Thermal Storage System Description

Dimensions of the thermal storage unit were: 450 mm in height and 300mm in diameter. A system has been designed to store 4MJ of solar energy in the form of thermal energy. The model of the system has been shown in Figure 3.24.

The system consists of five steel containers for the PCM, and the inside dimensions of each container are 25cm x 2.5cm x 35 cm. The thickness of the container material (steel) has been 1mm. It has been used for enhancing the rate of heat transfer in the PCM during charging and discharging.

CHAPTER FOUR

EXPERIMENTAL SETUP AND MEASUREMENTS PROCEDURE

4.1. Experimental Setup

The experimental setup (prototype) of the system has been shown in Figure 5.1. It consists of a conventional solar air heater with expanded mesh, latent heat energy storage (Paraffin wax) encapsulated inside the container below the eggs chamber and the eggs chamber. The axial type fan and PVC connection pipe with a diameter of 50mm have been used in between thermal energy storage unit and solar air heater for transporting Heat Transferring Fluid (HTF) or hot/cold air.

Figure 4.1 Solar Thermal Powered Incubator Systems

4.1.1. Eggs Chamber (Incubator)

The egg chamber has been made of two (2) layers. The wooden layer on the outside reduces the response of the heat release effect from the outside. The foam layer is covered with aluminum foil attached to the inside of the eggs chamber to reduce heat loss and give the heat reflection in the chamber. Its outside dimensions are 100cm long, 100cm wide, and 100cm depth and inner dimensions are 96cm long, 96cm wide, and 96cm high.

4.1.2. Charging and discharging of the Thermal energy storage

The storage of energy from a solar field is governed by the rate at which the energy can be brought to the thermal storage by the heat transfer fluid and the discharging times will be governed by the rate at which the stored energy is used [18].

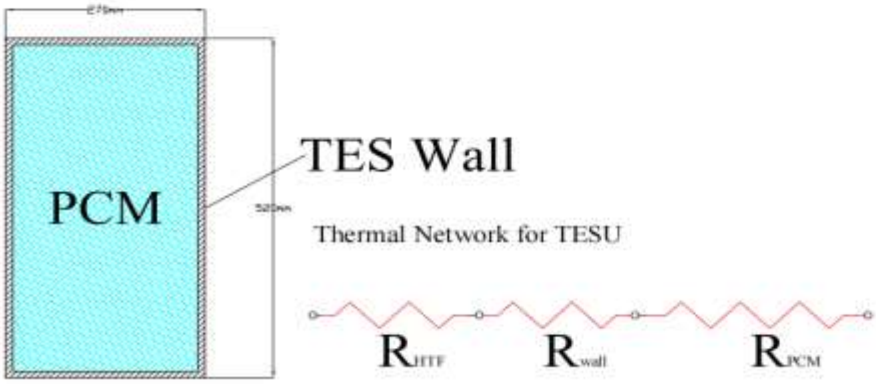


Figure 4.2 Thermal networks between PCM and TES wall

$$U = \frac{1}{\frac{1}{Rhtf} + \frac{1}{Rwall} + \frac{1}{Rpcm}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.1)$$

4.1.3. Charging and Discharging Process

As shown in Figure 6.6 the simulation has been done to identify the charging process of the TES system with ANSYS fluent 16.2. The total heat required to store in TES (paraffin wax) has been 4MJ. The discharging has been done with an output power of 40.89Watts to overcome the power lost through eggs chamber walls during the nighttime to keep incubator chamber temperature constant.

Discharging time has been assumed to be at least for 12hrs. Storage and discharging times into or out of thermal storage are mainly affected by the flow of HTF near the thermal storage unit. Zivkovic and Fujii (2000), do the mathematical model for the one-dimensional isothermal phase change of PCM encapsulated within rectangular containers as shown as Eqs (5.2), (5.3) & (5.4).

They represent the governing equation for the melting of PCM inside a rectangular container as follows. For the problem of isothermal phase change, the local liquid fraction f_l is defined as:

$$f_l = \begin{cases} 1 \text{ if } T > Tm \\ 0 \text{ if } T < Tm \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.2)$$

The enthalpy formulation for the conduction-controlled phase change can be written as:

$$\frac{\partial H}{\partial t} = div\left(\frac{k}{\rho} gradT\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.3)$$

For $\frac{\partial \mathrm{H}}{\partial \mathrm{t}} = \frac{\partial \mathrm{h}}{\partial \mathrm{t}} + \mathrm{L}\frac{\partial f1}{\partial \mathrm{t}}$ it can be written as: -

$$\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(\frac{k}{\rho} * \frac{\partial T}{\partial x}\right) - \mathrm{L}\frac{\partial f_1}{\partial \mathrm{t}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.4)$$

4.1.4. Egg Preparation

Before loading the eggs into the incubation chamber the following steps are carried out:-

1. Buying the eggs from the market
2. Selecting and handling the eggs
3. Cleaning and preparing the incubation chamber
4. Cleaning the eggs trays
5. Loading the eggs into the incubation chamber

4.2. Measurements Procedure

The factors affecting the performance of solar thermal powered egg incubator were presented with latent heat thermal energy storage (paraffin wax). These factors are including the thermal performance of the system energy storage during charging and discharging, the temperature of the eggs chamber temperature, eggs turning, and ventilation.

Figure 4.3 the thermocouple wires inserted into thermal energy material and for eggs chamber

The thermal performance of the system has been tested. It consists of the conventional flat plate solar collector (solar air heater), the latent heat storage, and the eggs chamber. Primarily the whole components of the system were checked whether they were functioned well or not. The experiments were carried out in Adama city weather condition (latitude of $8°32'$N, longitude of $39°22'$E), Ethiopia. The solar potential of the city has been theoretically estimated as shown in figures (3.1-3.16).

Figure 4.4 Calibrating the OMRON E5CSL thermocouple with standard lab WL 362 thermocouple

Calibrated temperature controller (Thermocouple) has been installed and used for measuring the temperature and used for controlling the chamber temperature by switching on/off the ventilation fan inside the eggs chamber. The temperature inside the eggs chamber must be between $35 - 39$℃ [**20**].

4.2.1. Uncertainty Analysis of Instrument

Any measurements are not perfectly accurate when we compare to the standard measurement. Hence uncertainty analyses are needed. Calibration compares an instrument's output against an accurate standard. Once an error is known, any deviations can be corrected. In this work, E5L OMRON thermometer could be calibrated and adjusted to show the system temperature in Celsius with WL 362 thermometer.

To calculate the RMS error, you first need to calculate the errors. Errors are the difference between the measured values (with OMRON) and the standard (WL 362) values. The two differences can be positive or negative. In this section, the measurement uncertainty and error of the instrument with the standard are described. The measured data are listed in Table A.1.

$$RMS\ Error = \pm\sqrt{\frac{\sum_{i=1}^{n}(T_{OMRON} - T_{WL\ 362})}{n}}$$

The average measurement error is less than ± 1.84℃. The result of calibration shows that the instrument is appropriate to use it.

CHAPTER FIVE
RESULTS AND DISCUSSIONS

5.1. Introduction

Experiments have been conducted to test the thermal performance of each component of the systems. The components are a solar air heater, system thermal energy storage unit, and eggs chamber. The calibrated OMRON E5LC thermocouple has been used for measuring the temperature of the system components.

5.2. Performance of Solar Air Heater

Figure 6.1, has been shown that the values of hourly air temperature leaving the solar air heater collected. It has been collected by starting from morning to 8 PM (at 2 AM Local time) and to 6 A.M (12 PM local time). The average hourly temperature has been measured as 54.0℃. The figure also illustrates that the maximum air temperature obtained is 75℃ during test 3.

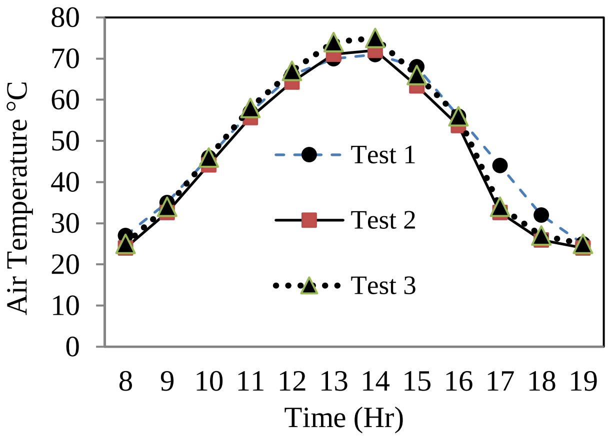


Figure 5.1 The Average air Temperature leaving the system solar collector

The figure presents that the hourly variation of the air temperature leaving the solar air heater. The maximum air temperature recorded during the tests was obtained at about 2 PM (8 A.M Local Time).

5.2.1. Air collector efficiency

Figure 5.3 shows that the system solar collector efficiency. The average efficiency of the system has been measured as 37.10% as shown in Table A.4.

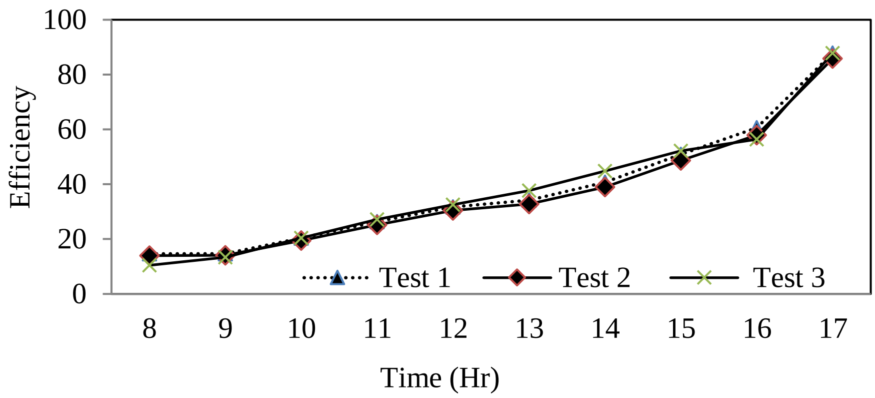


Figure 5.2 The system solar collector efficiency

5.3. Performance of the System Energy Storage

5.3.1. Experimental Result of the System Thermal Energy Storage

The below figures show that the charging and discharging effects of system thermal energy storage and analyzing and presenting the results. The thermocouple wires were inserted into the thermal storage containers at the length of 0%L, 25%L, 50%L, 75%L, and 100%L as shown on the schematic diagram in Figure 5.3. The temperature variation of the storage medium (paraffin wax) has been described in the following figures.

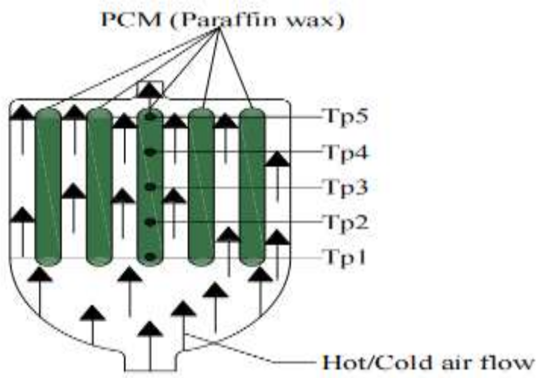


Figure 5.3 Schematic Diagram of the thermal energy storage unit

Figure 5.4 shows that the temperature variation of the thermal energy storage unit from the tip bottom to tip up. Tp1, Tp2, Tp3, Tp4, and Tp5 represent the temperature at the bottom end, at the length of 25%L, 50%L, 75%L, and at the top end (100% length) of the storage medium (Paraffin wax) the respectively. As the figures show the temperature variation of the thermal energy storage unit has been increasing upward from the bottom end to the top end.

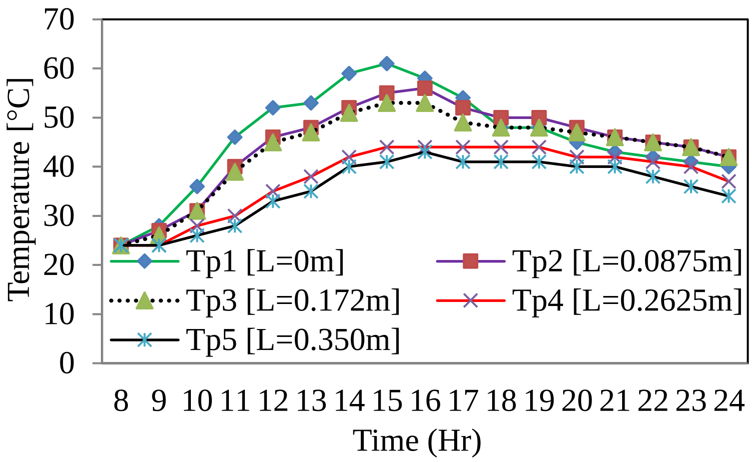


Figure 5.4 Average temperatures [℃] TES during charging and discharging

The maximum temperature attained by the storage has been 61℃ at the point Tp1. Its average temperature on the bottom and top portion are 58 and 43.5℃ respectively. This shows that the energy stored in the bottom portion is sensible and latent but in the upper portion it is only of sensible energy as shown in Figure 5.6.

Figure 5.5 shows that the comparison of temperature variation at each point of thermocouple wires during the charging process of the thermal energy storage unit. The temperature distribution of system thermal storage has been illustrated. During the process, the temperature at any position has been varying with time (hr) and increasing till 3 PM (at the local time 9 A.M).

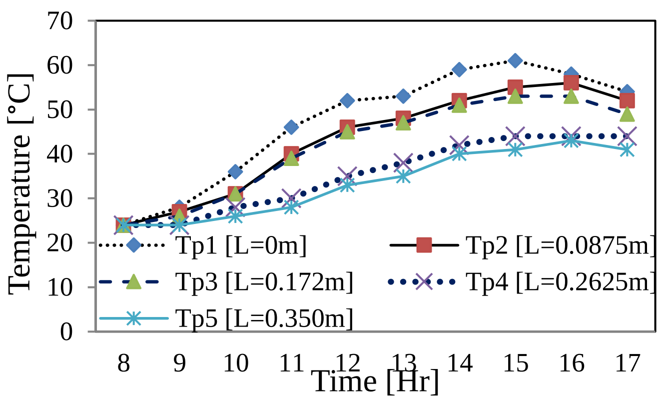


Figure 5.5 TES Temperature (℃) During Charging

The initial temperature of paraffin wax is 24℃. The graph represents that energy stored in the thermal energy storage at point Tp1, Tp2, and Tp3 is greater than at the point 4 and 5. This is because of the low conductivity of the storage medium material (paraffin wax).

The maximum temperature has been attained at Tp1 i.e. 61℃. The average temperature of at points Tp1, Tp2, and Tp3 are 58℃. This shows that half of the thermal energy stored in the thermal storage is in the form of latent heat.

From an experimental result; it has been observed that the maximum and minimum heating rate of PCM (Paraffin wax) during the charging process is 9℃/hr and 1℃/hr respectively for on the bottom and the top of the PCM. The heating rate of the system is identified from the temperature of the paraffin wax measured by using the K-type thermocouples list in Table A.1. The melting point of the commercially available paraffin wax is 57 − 59℃ **[47]**. The discharging process has been done with natural convection and the inlet temperature of the HTF of the atmospheric air temperature has been assumed to be 20℃. During the discharging process, the cold air is circulated through the encapsulated PCM (paraffin wax) to transfer the heat energy stored in PCM (paraffin wax) into HTF (air) for heating eggs and eggs chamber.

5.3.2. Energy Recovered by Thermal Storage Material

As shown in figure 5.7 paraffin wax average temperatures measured by thermocouples is 58℃ and 43.5℃ respectively on the lower and upper portion of the system. The energy recovered by a storage medium (the LHS system with a PCM medium (paraffin wax)) during the energy charging process has been calculated as the following by:

$$\mathrm{Q_{recovered}} = \int_{\mathrm{Ti}}^{\mathrm{Tm}} \mathrm{mCpdT} + \mathrm{m\Delta hm} + \int_{\mathrm{Tm}}^{\mathrm{Tf}} \mathrm{mC_p dT}$$

$$\mathrm{Q_{recovered}} = (\mathrm{mC_p dT} + \mathrm{m(\Delta h_m)_{lower}} + (\mathrm{mC_p dT})_{\mathrm{upper}}$$

For calculating the energy recovered by the system thermal storage an average temperature of the paraffin wax inside the storage unit has been taken from above and below half the portion. The recovered thermal energy in the thermal storage medium is assumed to be equal to the total energy stored in the upper and lower portion of the storage system unit.

Therefore:

$$Q_{recovered} = (m_{lower} * C_p * (T_{lower} - T_{initial}) + m_{lower} * \Delta h_m)_{lower} + (m_{upper} * C_p * (T_{lower} - T_{initial}))_{upper}$$

$$Q_{recovered} = ((7.5\ kg) * (2100 kJ/kg * ℃) * (58℃ - 20℃) + (7.5\ kg) * (199{,}000\ kJ/kg))_{lower} + (7.5kg * 2000kJ/kg * ℃) * (43.5℃ - 20℃))_{upper}$$

$$Q_{recovered} = 2{,}443{,}500J \approx 2.44MJ$$

$\%Q_{recovered} = \frac{Q_{recovered}}{Q_{required}} * 100\% = \frac{2.44MJ}{4MJ} * 100\% = 61.10\%$; The calculation shows that 61.10% of the energy required for the system operation has been recovered.

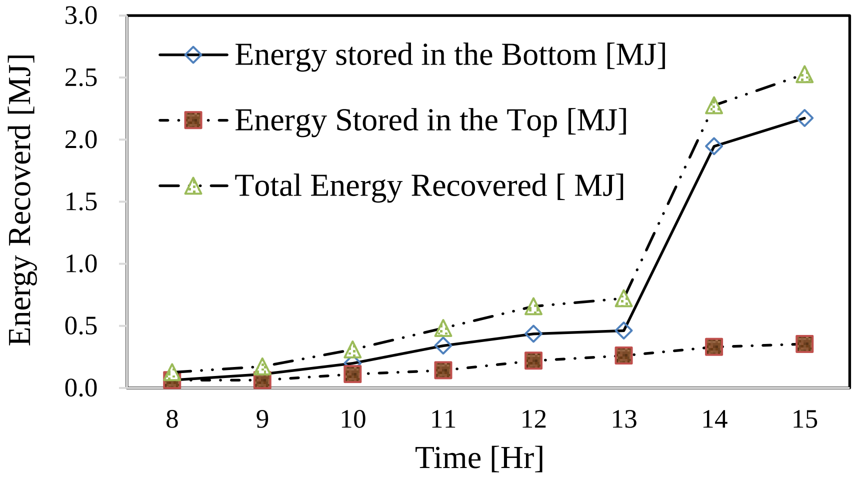


Figure 5.7 The thermal energy recovered by TES

Figures 6.8 Show the heat discharging effect of thermal energy stored in the system thermal energy storage. The temperature of the thermal storage at any position of thermocouple wires has been measured with an interval of one hour.

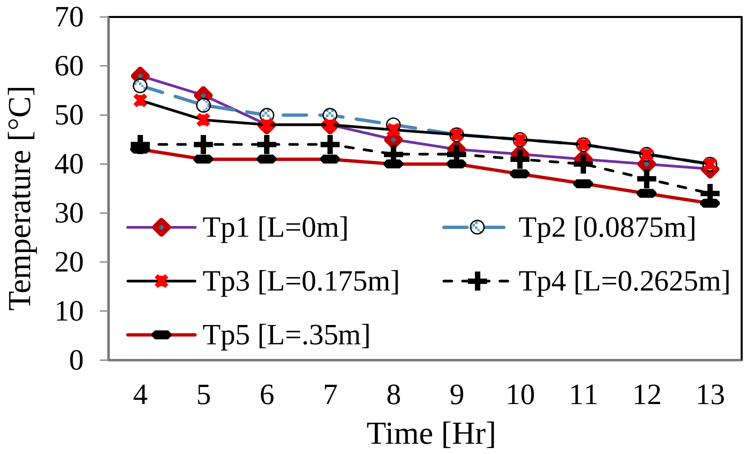


Figure 5.8 Temperature Variation of Energy Storage vs. Hour during discharging

5.4. Thermal Performance of Eggs Chamber with no load

In this section, the hourly temperature of the eggs chamber collected has been presented as shown in Appendix A. It shows that the egg's chamber temperature was collected on March 31, April 4, and April 8, 2021.

Figure 5.9 Chamber Temperatures during Day Time

It shows that the average of eggs chamber temperature has been ranged from 24 to 43.00℃.

Figure 5.10 Chamber Temperatures during Day Time and middle night

During the test, the average temperature of the eggs chamber at the midnight has been below the system operating temperature as shown in Figure 5.10. Therefore, it illustrates that additional thermal energy sources must be needed to sustain the system energy demand. The average temperature of the eggs chamber obtained has been an average of 34℃ with a deviation of 5℃ as shown in Figure 5.10.

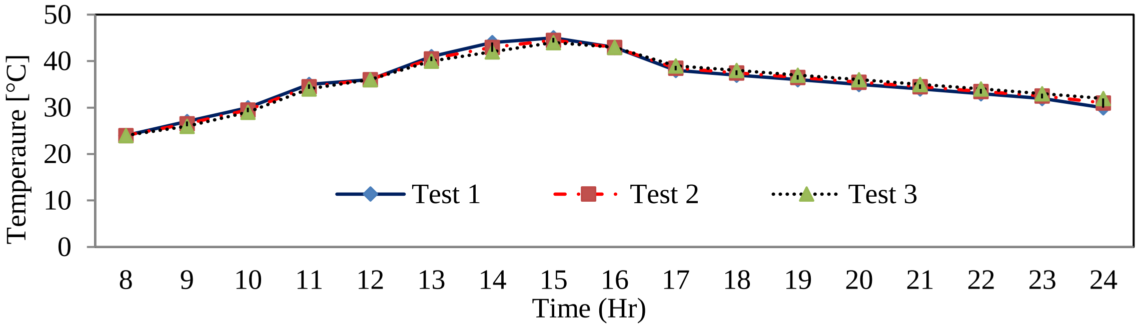


Figure 5.11 The hourly chamber temperature without loading the egg

5.4.1. The Relative Humidity of the Chamber

The average relative humidity of the egg chamber is predicted as 66%RH. The relative humidity of the system is predicted by using the dry bulb and wet bulb temperature collected during the process. Many works of literature describe that the moisture level in the incubator should be about 50 to 70 percent with an increase to about 65-70 percent for the last 3 days of incubation. Moisture is provided by a pan of water under the egg tray [**19**].

5.5. Thermal Performance of Eggs Chamber with load

5.5.1. Test - 1

In the first test, the ten chicken eggs are selected and loaded into the incubation chamber on April 12. The system has been tested with 10 eggs. After 2nd week of incubation, the two eggs are checked. During the test process, the two eggs are drawn off from the incubation chamber and checked by breaking them to see whether the chicken embryos are developing or not. Therefore, as shown in figure 5.12 the two eggs are starting to be developing into a chicken.

For the success rate of egg hatching to be high the egg incubator system must be able to maintain the temperature and level it in the chamber. The ideal temperature for hatching chicken eggs is around $35 - 39°C$ and 60% humidity. The result shows the chamber temperature is insufficient so that the egg embryo development is retarded and also because of rain falling during incubation (April 27th the rain has been started raining continuously up to May 5). The condition made developing eggs embryos to have died.

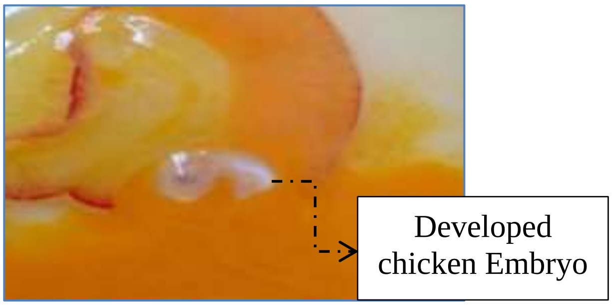


Figure 5.12 Developed chicken egg embryo after 14 days of incubation

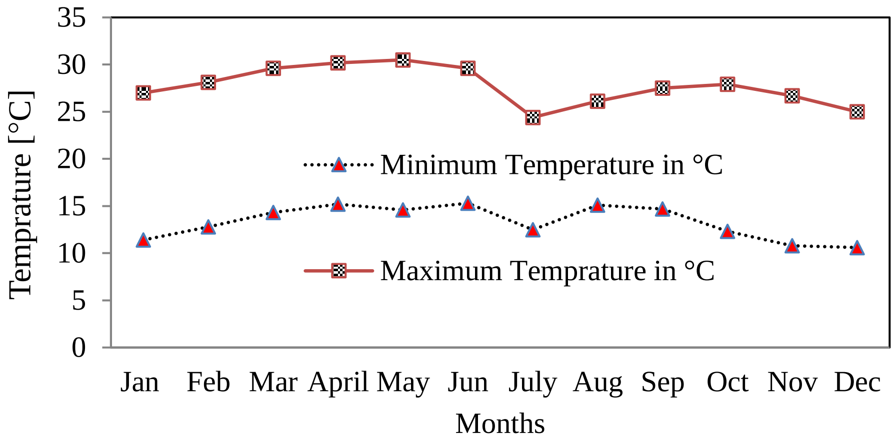


Figure 5.14 The monthly average minimum and maximum temperature of Adama, Ethiopia

5.5.2. Test - 2

Based on the 1st test, three kilograms of paraffin wax have been used as additional energy storage with a 200Watts electric heater. The electric heater has been used to melt the paraffin wax for an additional source of heat for the system. In doing this the result obtained from the system during the process has been described as follows. The second test has been conducted from May 22 to June 17 with ten eggs that are purchased from the market and loaded into the eggs chamber as shown in Figure 6.15. Figure 6.16 illustrates that the developing progress of chicken egg embryos. The figures show that how the eggs cell has been developing into a chicken embryo.

Figure 5.14 The eggs loaded into the incubation chamber

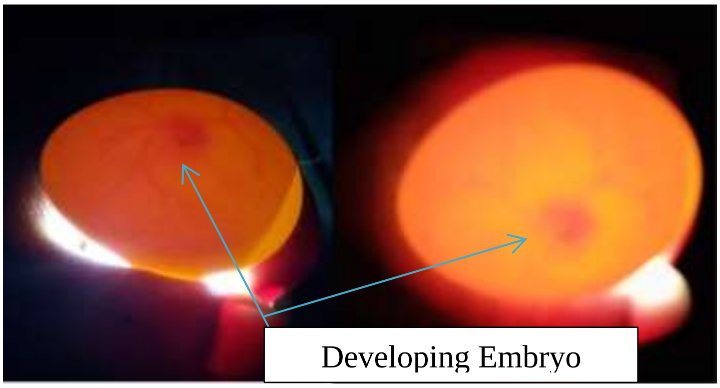


Figure 5.15 shows that developing chicken embryo inside eggshell in the first week

Figure 5.15 illustrates that the embryo developing inside the egg's shell. Among loaded eggs into incubation chamber, four (4) eggs are starting to develop into a chicken embryo. It shows that the development of the embryo after one week of the incubation period.

Figure 5.16 successfully hatched eggs by the system embryo

After 18 days of incubation, the eggs are put on the hatching tray since the egg turning is not needed.

Figure 5.17 Unsuccessful or dead chicken egg

$$\bar{T} = \frac{1}{N}\sum_{n=1}^{N} T_m = 34℃;\ \delta_T = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(\bar{T} - Tm)^2} = 5℃$$

$$Percentage\ of\ hatchablity\ (Success) = \frac{Hatch}{loaded\ eggs\ into\ the\ chamber} * 100\% = 20\%$$

Among the ten eggs load into the incubation chamber, 2 of them (two eggs) are successfully hatched as shown in Figure 5.18. This shows that the success rate of hatching reached 20% of the eggs loaded into the system.

5.6. Cost Analysis of the Project

The cost of the project is estimated as listed in the following table. The cost for building the overall systems varies significantly depending on the materials purchased used to construct. Capital and maintenance costs for the project work were described in Table 6.1. By doing this work that the benefits obtained from the project are estimated by using the following equation. The maintenance cost of the project is assumed to be 10% of the sum cost of each component of construction cost.

Table 5.1 Capital and maintenance costs

Components of the System	Component Costs	Annual Maintenance Costs (ETB)	Total Net Present Worth (ETB)
Solar air heater	3500	350	Transportation Cost in ETB 350
Thermal energy storage unit with PCM	2500	250	
Chamber	1500	150	
Eggs Turner	1000	100	
Thermocouple & Fans	3500	350	
Total Cost in ETB	12,000	1,200	Total = 13550

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATION

6.1. Conclusion

In this work, a detailed experimental study has been conducted to evaluate the performance of the solar thermal chicken egg incubator with thermal energy storage for hatching chicken eggs.

The study has been conducted under Adama city (latitude of $8°32'N$, longitude of $39°22'E$), Ethiopia weather condition. Experiments were conducted to study the performance of the whole components of the solar thermal-powered eggs incubator systems. The overall efficiency of the system is evaluated. The system contains three main components. They are a solar air heater, thermal energy storage unit, and Eggs chamber.

The average air temperature leaving the solar air heater is $52℃$ and with the maximum and minimum of 75 and $27℃$ respectively. It is a very important component of the system. It has been used as the thermal energy source for the thermal storage materials; hence heating the egg chamber for egg incubation. Paraffin wax enclosed within a rectangular container has been used as latent heat energy storage of the system. The 15 kg of paraffin wax has been used for storing the thermal energy for the system, but only 61.10% (percent) of energy required by the system is recovered by the system. The average incubator chamber temperature has been obtained as $34℃$ with a mean deviation of $5℃$. Three kilograms of paraffin wax has been used as an additional energy source with a 200Watts electric heater. By doing this the result obtained from the system has been reached with an average eggs hatching ability of only 20% of the loaded eggs.

Since thermal efficiency reduction of the system is affects the chicken eggs hatching ability of the system; it is better to use an auxiliary heat source (like a PV subsystem).

6.2. Recommendation for the Future Work

The solar thermal energy system is very appropriate for egg incubators in case solar radiation is readily available. The ambient temperature is the main factor affecting the system's efficiency. Supported to the conclusions and works of literature reviewed the following recommendations are made:

- The heat is insufficient to maintain the system temperature for 24 hours; therefore the attention should be given to solar air heaters and thermal energy storage since their efficiency directly affects the thermal efficiency of the system.
- There should be adequate thermal energy storage for the system that to store enough energy for the system operation.
- It is better to use small size thermal storage casings for encapsulating the storage medium, hence increasing the rate of heat transfer in between PCM and heat transferring fluid (HTF).
- It may have the potential of drying the crop; since the maximum air temperature leaving the solar air heater is 75℃.

6.3. Limitation

The system has been designed by assuming an ambient temperature (external weather condition) greater than 20℃. But the weather condition of Adama, Ethiopia during night time as well as the cloudy day becomes below assumed temperature as shown in Figure 5.14. This condition might affect the system's efficiency and operation. Therefore energy lost by the system during the work becomes very higher than the assumption taken while designing. Hence the additional source of thermal energy is needed for successful system operation.

6.4. Design of PV subsystem for the System

The above sections show that the heat delivered by the system is insufficient to maintain the system temperature for 24 hours; therefore in this section, an additional auxiliary heat source for the system i.e. PV subsystem is designed to overcome the energy insufficiency of the system. This may solve the problem. The energy load in the system has been estimated as 50Watts to be powered by PV subsystem for at least for 8hr per day to fulfill the system power insufficiency during the process. The study has been done under Adama, Ethiopia weather Conditions. The total average sunshine hours in this town is estimated as 7hr or 25200sec.

Energy consumption of the system during the time will be:

$$Q_{load} = \dot{Q}_{load} * \Delta t_{ot}$$

$$Q_{load} = 50Watts * (8hr * \frac{3600sec}{1hr}) \approx 1440000Joules$$

where: Q_{load} and Δt_{ot} are the total energy consumed by the system and operational time of the PV subsystem respectively.

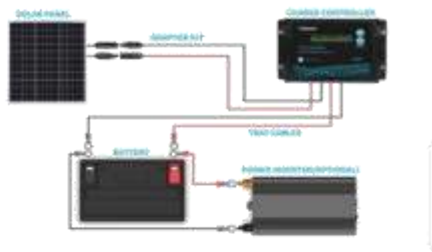


Figure 6.1 PV Subsystem Components (www.amazon.com/PV system/)

Therefore the size of the solar panel module is calculated as follows:

$$Sizes\ of\ solar\ modules\ in\ watts = \frac{Q_{load}}{Ns} = \frac{1440000Joules}{25200sec} = 57.14Watts$$

Thus; 100Watts power rating of solar power would be selected for the system.

To determine the size of the battery (total capacity) the equation below was used:

$$The\ size\ of battery = \frac{Total\ energy\ requirement\ for\ period\ pv\ operate}{Norminal\ battery\ voltage}$$

The sunshine hours are 7hrs and the PV subsystem operating time is 8hrs. Taking the nominal battery voltage as 12Volts the size of the battery was calculated:

$$The\ Size\ of\ Battery = \frac{\left(\frac{1440000Joules}{Period\ of\ pv\ operation}\right)}{12volts} * \left(\frac{25{,}200sec}{28{,}800sec}\right) = 105{,}000Ampsec \approx 30Ahr$$

$$The\ size\ of solar\ controller\ in\ Amps = \frac{100Watts}{12Volts} = 8.3333Amps$$

The size of the solar charge controller that would be needed is 10Amps. Also, the size of the solar inverter that would be selected is 100Watts

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Appendix - A

A.1. Calibration of Thermo couple

This section contains the calibrating data of thermocouples used for the work and measured system component's temperature and results. It has been performed with both water heating and cooling process. The standard WL 362 digital thermocouple in the thermal laboratory has been used to compare with it.

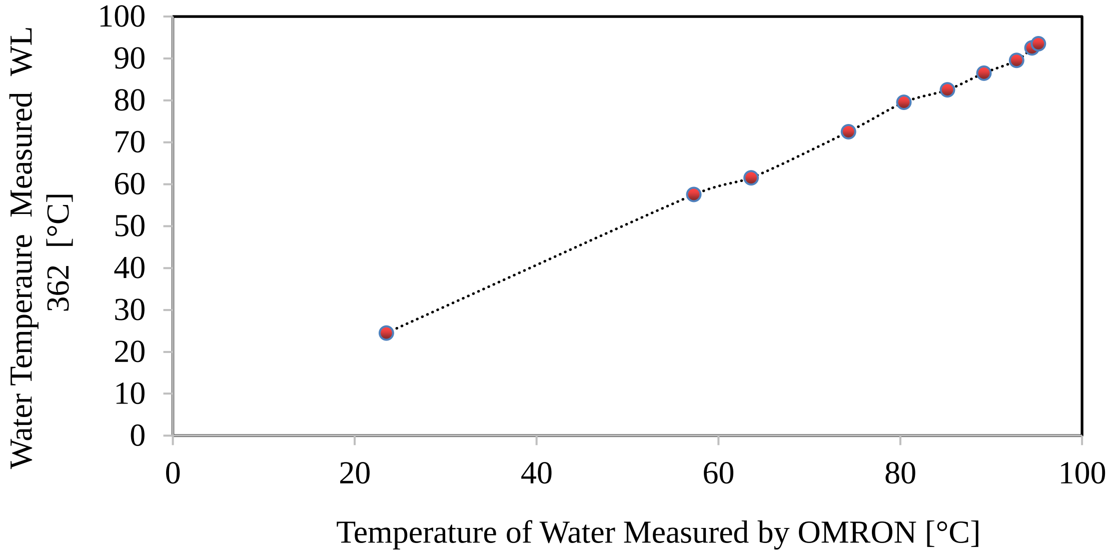

Figure A.1. OMRON (H-Tested) with WL 362 by heating water testing effect

Table A.1 Water Heating test effect

Water Heating test effect						
t(Minute)	t(sec)	WL 362(Actual)	OMRON(H-Tested)	Average	Error	%Error
0	0	23.5	24.5	24	-1.00	4.255
5	300	57.3	57.5	57.4	-0.20	0.349
10	600	63.6	61.5	62.55	2.10	3.302
15	900	74.3	72.5	73.4	1.80	2.423
20	1200	80.4	79.5	79.95	0.90	1.119
25	1500	85.2	82.5	83.85	2.70	3.169
30	1800	89.2	86.5	87.85	2.70	3.027
35	2100	92.8	89.5	91.15	3.30	3.556
40	2400	94.5	92.5	93.5	2.00	2.116
45	2700	95.2	93.5	94.35	1.70	1.786

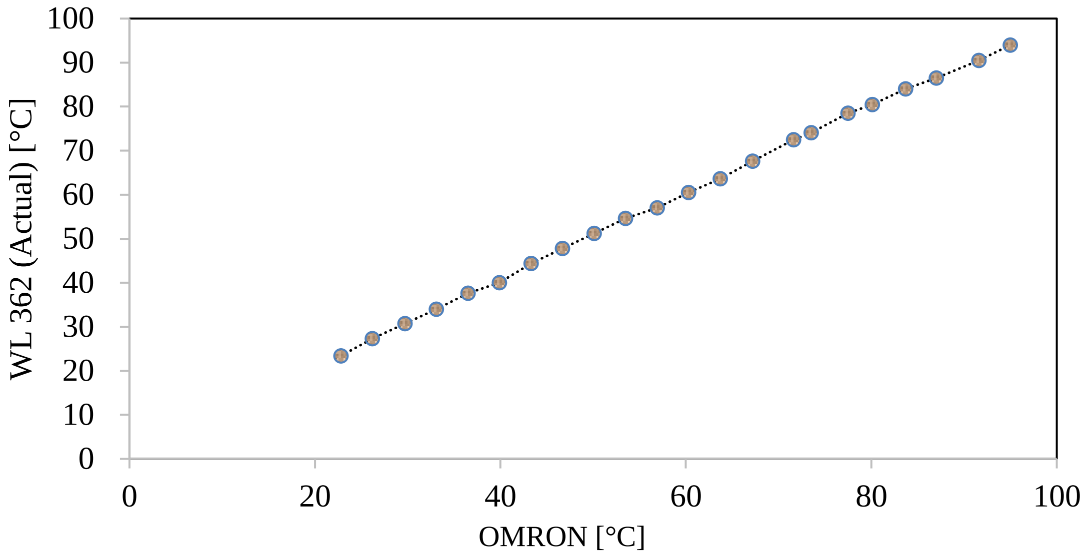

Figure A.2. OMRON vs. WL 362 (Actual) for water cooling effect

Table A.2. Calibration of thermocouples

	Water Cooling test effect					
t(Min)	t(sec)	WL 362(Actual) [°C]	OMRON (Tested) [°C]	Average [°C]	Error [°C]	%Error
0	0	95	94	94.5	1	1.1
3	180	91.6	91	91.1	1.1	1.2
6	360	87	87	86.8	0.5	0.6
9	540	83.7	84	83.9	0.3	0.4
12	720	80.1	81	80.3	0.4	0.5
15	900	77.5	79	78.0	1	1.3
18	1080	73.5	74	73.8	0.6	0.8
21	1260	71.6	73	72.1	0.9	1.3
24	1440	67.2	68	67.4	0.4	0.6
27	1620	63.7	64	63.7	0.1	0.2
30	1800	60.3	61	60.4	0.2	0.3
33	1980	56.9	57	57.0	0.1	0.2
36	2160	53.5	55	54.1	1.1	2.1
39	2340	50.1	51	50.7	1.1	2.2

42	2520	46.7	48	47.3	1.1	2.4
45	2700	43.3	44	43.9	1.1	2.5
48	2880	39.9	40	40.0	0.1	0.3
51	3060	36.5	38	37.1	1.1	3.0
54	3240	33.1	34	33.6	0.9	2.7
57	3420	29.7	31	30.2	1	3.4
60	3600	26.2	27	26.8	1.1	4.2
63	3780	22.8	23	23.1	0.6	2.6
					Aver: -	1.5%

Table A.3. Air Temperature Leaving Collector [℃ **]** recorded

Time Hour	Air Temperature [℃] Test 1	Air Temperature [℃] Test 2	Air Temperature [℃] Test 3
8	27	26	27
9	35	34	35
10	46	45	46
11	57	56	57
12	66	64	66
13	70	68	70
14	71	69	71
15	68	66	68
16	56	55	56
17	44	43	44
18	25	30	25
19	23	25	23

Table A.4. The Solar air collector efficiency

Time	Iaver	SAH DT 1	SAH DT 2	SAH DT 3	Qo [Kw] Test 1	Qo [Kw] Test 2	Qo [Kw] Test 3	Efficiency Test 1	Efficiency Test 2	Efficiency Test 3
6	0	-	-	-	0	0	0	-	-	-
7	0	-	-	-	0	0	0	-	-	-
8	0	-	-	-	0	0	0	-	-	-
9	0	-	-	-	0	0	0	-	-	-
10	0	-	-	-	0	0	0	-	-	-
11	0	-	-	-	0	0	0	-	-	-
12	0.01	-	-	-	0	0	0	-	-	-
13	0.19	-	-	-	0	0	0	-	-	-
14	0.43	7	6	5	0.063	0.060	0.05	14.6	14.0	10.5
15	0.67	11	10	10	0.098	0.094	0.09	14.7	14.1	13.4
16	0.88	20	19	20	0.179	0.172	0.18	20.4	19.5	20.4
17	1.02	30	29	31	0.268	0.258	0.28	26.3	25.3	27.2
18	1.07	38	36	39	0.34	0.326	0.35	31.8	30.5	32.6
17	1.02	39	37	43	0.349	0.335	0.39	34.2	32.8	37.7
18	0.88	40	38	44	0.36	0.343	0.39	40.8	39.0	44.9
19	0.67	38	36	39	0.34	0.326	0.35	50.9	48.7	52.2
20	0.43	29	28	27	0.265	0.249	0.24	60.6	57.9	56.5
21	0.19	19	18	19	0.17	0.163	0.17	87.8	85.9	87.8
22	0.01	-	-	-	0	0	0	-	-	-
23	0	-	-	-	0	0	0	-	-	-
24	0	-	-	-	0	0	0	-	-	-
1	0	-	-	-	0	0	0	-	-	-
2	0	-	-	-	0	0	0	-	-	-
3	0	-	-	-	0	0	0	-	-	-
4	0	-	-	-	0	0	0	-	-	-
5	0	-	-	-	0	0	0	-	-	-

Table A.5. Charging and discharging effects of thermal energy storage

Time [Hr]	Tp1	Tp2	Tp3	Tp4	Tp5	Avrg: Temp [℃] on the Bottom Portion	Avrg: Temp [℃] on the Top Portion
8	24	24	24	24	24	24.0	24
9	28	27	26	24	24	27.0	24
10	36	31	31	28	26	32.7	27
11	46	40	39	30	28	41.7	29
12	52	46	45	35	33	47.7	34
13	53	48	47	38	35	49.3	36.5
14	59	52	51	42	40	55.0	41

15	61	56	55	44	41	57.3	43
16	58	56	53	44	43	55.7	43.5
17	54	52	49	44	41	51.7	42.5
18	48	50	48	44	41	48.7	42.5
19	48	50	48	44	41	48.7	42.5
20	45	48	47	42	40	46.7	41
21	43	46	46	42	40	45.0	41
22	42	45	45	41	38	44.0	39.5
23	41	44	44	40	36	43.0	38
24	40	42	42	37	34	41.3	35.5
1	39	40	40	34	32	39.7	33

Table A.6. TES Temperature (℃) During Charging Process of TES (Paraffin Wax)

TES Temperature (℃) During Charging					
Time [Hr]	Tp1	Tp2	Tp3	Tp4	Tp5
8	24	24	24	24	24
9	28	27	26	24	24
10	36	31	31	28	26
11	46	40	39	30	28
12	52	46	45	35	33
13	53	48	47	38	35
14	59	54	51	42	40
15	61	58	55	44	41
16	59	58	55	44	43

Table A.8. Discharging Process of TES (Paraffin Wax)

Time [Hr]	Tp1	Tp2	Tp3	Tp4	Tp5
16	58	56	53	44	43
17	54	52	49	44	41
18	48	50	48	44	41
19	48	50	48	44	41
20	45	48	47	42	40
21	43	46	46	42	40
22	42	45	45	41	38
23	41	44	44	40	36
24	40	42	42	37	34

Table A.9. The hourly chamber temperature collected on Test one (without load)

Time [Hr]	T_{Ch1}	T_{Ch2}
8	24	27
9	29	30
10	32	33
11	36	36
12	40	38
13	42	41
14	46	43
15	48	47
16	49	47
17	43	43
18	39	39
19	37	37
20	36	36
21	34	35
22	33	34
23	32	33

24	30	32

Table A.10 the hourly chamber temperature without loading the egg on Test two (without load)

Time [Hr]	T_{ch1}	T_{ch2}
8	24	24
9	27	26
10	30	29
11	35	34
12	36	36
13	41	40
14	44	42
15	45	44
16	43	43
17	38	39
18	37	38
19	36	37
20	35	36
21	34	35
22	33	34
23	32	33
24	30	32

Table A.11 the hourly chamber temperature without loading the egg on Test three (without load)

Time [Hr]	T_{ch1}	T_{ch2}
8	25	24
9	29	27
10	32	30
11	35	34
12	39	36
13	41	40
14	45	43
15	48	44
16	47	43
17	43	39
18	38	38
19	37	37
20	36	36
21	34	35
22	33	36
23	32	33
24	30	31

Table A.12. Shows the average Eggs chamber Temperature collected in each hour (with load).

Time [Hr]	T_{ch} (Test 1)	T_{ch} (Test 2)	T_{ch} (Test 3)
8	24	23	21
9	24	23	23
10	25	24	26
11	28	25	28
12	35	25	31
13	36	26	33
14	38	26	36

15	40	32	38
16	42	35	41
17	42	35	41
18	41	33	39
19	39	33	37
20	37	32	35
21	36	31	34
22	34	29	32
23	33	27	31
24	31	26	30

Table A.13 The Average RH, Dry bulb, and wet bulb Temperature estimated inside the egg chamber

Time [Hr]	DBT [℃]	WBT [℃]	RH of Chamber
8	24	23	72.5%
9	24	23	72.5%
10	25	24	74%
11	28	25	81%
12	35	26	78%
13	36	30	80%
14	38	32	65%
15	40	33	64%
16	42	33	60%
17	42	33	61%
18	41	32	61%
19	39	32	56%
20	37	31	58%
21	36	29	55%
22	34	27	64%
23	33	26	58%

Appendix – B

Table B.1. SunShine Hour and the average monthly sunshine hour (ns)

Daily Hour	Months of the Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	Average Sun Shine Hour(ns)	9.17	9.34	9.06	8.4	8.17	8.012	6.76	6.93	7.49	8.96	9.26	9.57

Table B.2. The Value of Solar Power Data of Adama, Ethiopia

S/No	1	2	3	4	5	6	7	8	9	10	11	12
Month	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
n	17	47	75	105	135	162	198	228	258	288	318	344
Isc	1367	1367	1367	1367	1367	1367	1367	1367	1367	1367	1367	1367
Ø	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
COS Ø	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989
SINØ	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148
bop	33.5	23.8	11.0	-3.3	-14.4	-19.2	-16.2	-6.3	7.5	21.7	32.3	36.4
d	-20.9	-13.0	-2.4	9.4	18.8	23.1	21.2	13.5	2.2	-9.6	-18.9	-23.0
COSd	0.934	0.975	0.999	0.987	0.947	0.920	0.932	0.973	0.999	0.986	0.946	0.920
SINd	-0.357	-0.224	-0.042	0.164	0.322	0.392	0.361	0.233	0.039	-0.167	-0.324	-0.392
Rad d	-0.365	-0.226	-0.042	0.164	0.328	0.403	0.370	0.235	0.039	-0.168	-0.330	-0.402
COS(w)	0.057	0.035	0.006	-0.025	-0.051	-0.064	-0.058	-0.036	-0.006	0.025	0.051	0.064
ws	86.7	88.0	89.6	91.4	92.9	93.7	93.3	92.1	90.3	88.5	87.1	86.3
Cos w	0.057	0.035	0.006	-0.025	-0.051	-0.064	-0.058	-0.036	-0.006	0.025	0.051	0.064
R(w)	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5
Ho(MJ/m2/Day)	35.7	37.0	37.5	36.4	34.4	33.1	33.6	35.3	36.8	36.9	35.9	35.1
Ns(hr)	11.56	11.74	11.95	12.19	12.39	12.49	12.44	12.27	12.04	11.81	11.61	11.51
ns(hr)	9.17	9.34	9.06	8.4	8.17	8.012	6.76	6.93	7.49	8.96	9.26	9.57
ns/Ns	0.79	0.80	0.76	0.69	0.66	0.64	0.54	0.56	0.62	0.76	0.80	0.83
a	0.235	0.236	0.224	0.201	0.192	0.186	0.154	0.161	0.180	0.224	0.236	0.247
b	0.690	0.688	0.714	0.762	0.783	0.795	0.863	0.848	0.809	0.713	0.687	0.663
a1	0.634	0.644	0.657	0.670	0.681	0.687	0.684	0.675	0.662	0.648	0.637	0.631
b1	0.447	0.437	0.425	0.412	0.402	0.397	0.399	0.408	0.420	0.433	0.444	0.449
H(MJ/m2/Day)	27.9	29.0	28.7	26.4	24.4	23.1	20.9	22.6	25.1	28.3	28.1	28.1
Mt	0.782	0.783	0.765	0.726	0.708	0.696	0.623	0.640	0.682	0.765	0.784	0.799
Hd	7.62	7.91	7.83	7.22	6.65	6.30	5.71	6.17	6.86	7.71	7.68	7.66
Hb	20.30	21.07	20.84	19.23	17.70	16.77	15.20	16.44	18.27	20.54	20.45	20.40
b	25	25	25	25	25	25	25	25	25	25	25	25

ws''	96.49	93.90	90.72	87.19	84.23	82.76	83.42	85.94	89.34	92.87	95.81	97.23
Rb	1.24	1.13	1.00	0.86	0.75	0.70	0.72	0.81	0.94	1.09	1.21	1.28
Rd	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Hbb	25.25	23.83	20.81	16.53	13.26	11.68	10.95	13.36	17.24	22.33	24.83	26.05
Hdb	7.27	7.54	7.46	6.88	6.34	6.00	5.44	5.88	6.54	7.35	7.32	7.30
Hr	3.91	4.05	4.10	3.98	3.76	3.62	3.67	3.86	4.03	4.04	3.92	3.84
Hb	36.43	35.42	32.37	27.39	23.36	21.30	20.06	23.10	27.81	33.72	36.07	37.19
								Average Radiation				29.52

Table B.3. Thermo-physical properties of some solid materials for sensible heat storage in thermal system

Material	Temperature Range (℃)	Density (r) (kg/m^3)	Specific heat Cp (kJ/kg*K)	Thermal Conductivity (K) (W/kg*K)
Brick	20-70	1600	0.84	1.20
Concrete	20-70	2240	1.13	0.9-1.3
Wood	Up to 160	800	2.09	0.16
Aluminum	>>	2707	0.90	20.4
Stone, Granite	>>	2640	0.82	1.70-3.98
Stone, Sandstone	>>	2200	0.71	1.83

B.1. Figures of the Work Process

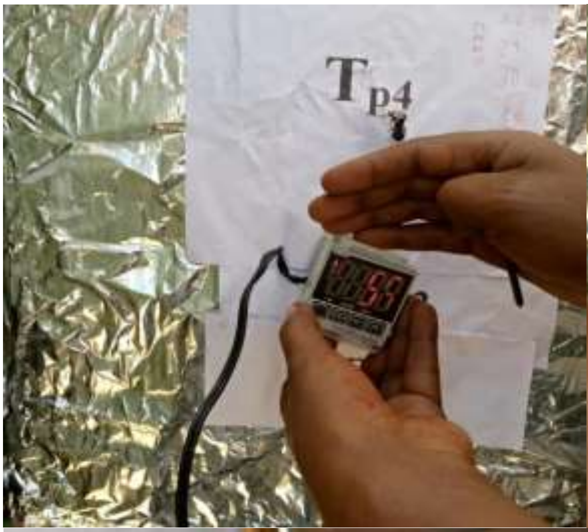


Figure B.1 Experimental set up for TESU and Eggs Chamber of the system.

Psychrometric Chart

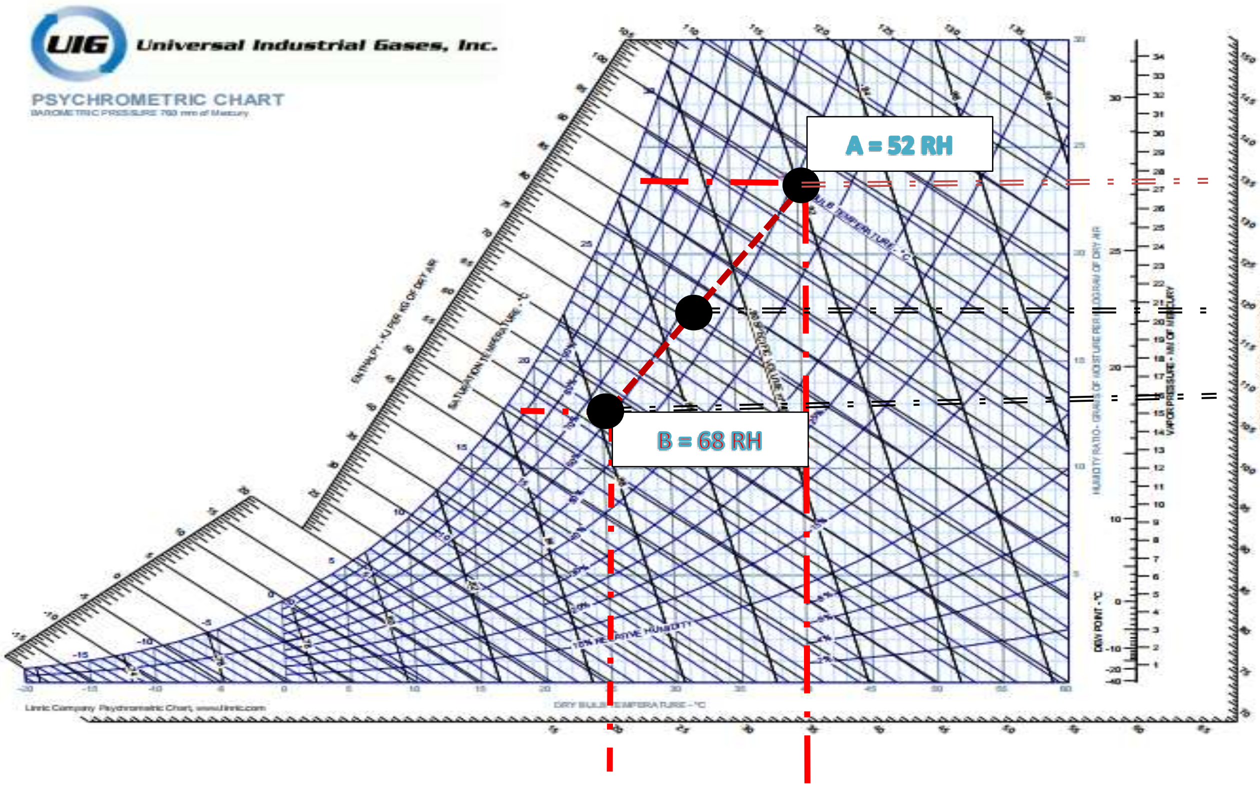

Figure B.2 Psychrometric Chart

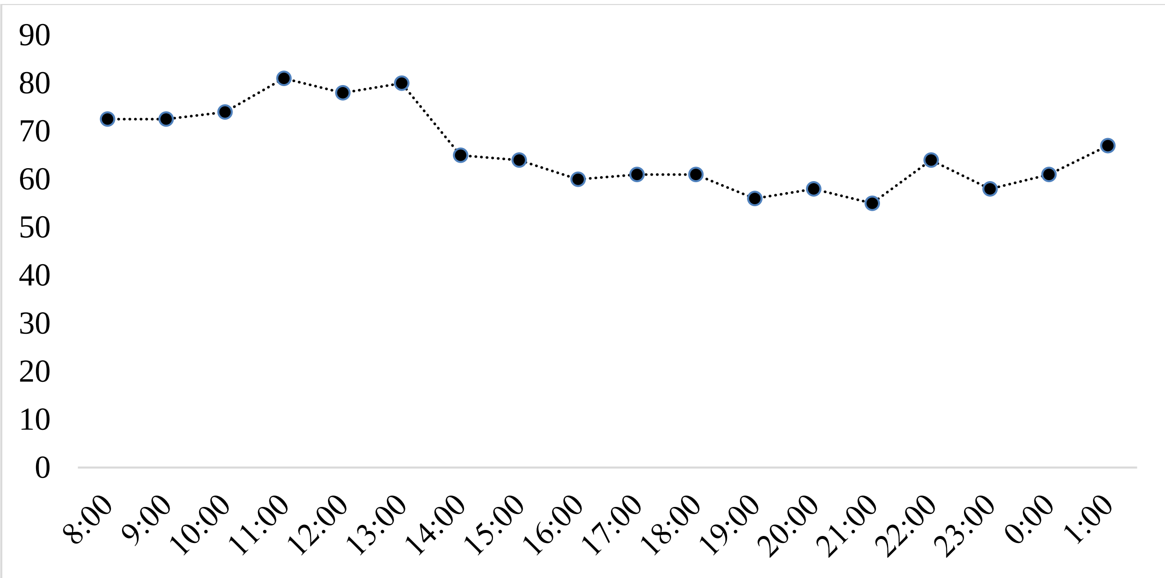

Figure B.3 Relative humidity of the egg chamber