A

Dissertation Report

On

Design, Development and Performance Analysis of Fin Type Solar Air Heater with and without Thermal Heat Storage

By

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Under the guidance of

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CERTIFICATE OF DISSERTATION SUPERVISOR

This is to certify that the dissertation entitled **"Design, Development and Performance Analysis of Fin Type Solar Air Heater with and without Thermal Energy Storage**" is being submitted by **Mr. Chandrapal Singh Inda, (2015PTE5162)** as requirement for partial fulfillment of award of the degree of **Master of Technology, Energy Engineering, Mechanical Engineering Department,** Malaviya National Institute of Technology, Jaipur is found to be satisfactory and is hereby approved for submission.

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DECLARATION

I **Chandrapal Singh Inda** declare that the dissertation entitled **"Design, Development and Performance Analysis of Fin Type Solar Air Heater with and without Thermal Energy Storage"** being submitted by me in partial fulfillment of the degree of **M. Tech (Thermal Engineering)** is a research work carried out by me under the supervision of **Prof. Dilip Sharma** and the contents of this dissertation work, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma. I also certify that no part of this dissertation work has been copied or borrowed from anyone else. In case any type of plagiarism is found out, I will be solely and completely responsible for it.

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ABSTRACT

From the last few decades the demand of energy is continuously increasing. Renewable energy is an alternative source of energy which can be useful to meet the difference between the supply and demand of energy. Solar is an effective renewable energy source for a region like Rajasthan that is blessed with high solar radiation. Due to its simplicity flat plate collector has gaining more popularity. Solar air hater is type of flat plate collector which utilizes solar energy into thermal energy to heat the air. Use of thermal energy storage gaining importance with the solar based applications since it can be very helpful in improving the performance of the solar collectors. Energy stored in the form of heat and cold can be use later. Solar energy can be collected by means of absorbing solar radiation therefore absorber plate is used in flat plate collector. Solar air heater is a flat plate collector i.e. use for transfer collected heat to air. Solar air heater is used for the purpose of space heating and drying the crops, seeds, etc.

In the present study newly designed fin type solar air heater integrated with thermal energy storage has been used for experiment. Some modification was done on the absorber plate like; fins were added and act as a storage tank. Relationship between number of fins and height of fins was developed. Performance of fin type solar air heater integrated with thermal energy storage was examined in MNIT, Jaipur (INDIA). Various temperatures measured on the absorber plate and glass cover were presented. Setup was examined for two different air velocities i.e. 2.5 m/sec and 3 m/sec. It was found that Heat gain for *solar air heater without thermal energy storage* was more at particular instant of time. But for complete day total heat gain was more for *solar air heater with thermal energy storage* for both air flow rate.

Performance analysis of solar air heater with and without thermal energy storage was the objective of the work. Improvement in the performance was found when thermal energy storage medium used. Improvement for both air flow velocities 2.5 m/sec and 3 m/sec was 14.08 % and 16.89 % respectively.

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Nomenclature

A	Actual heat transfer surface area [m^2]
A_f	Area of the fins surface [m^2]
C_p	Specific heat [J/kg-K]
D	Inside diameter ducts pipe [m]
h	Heat transfer coefficient [W/m^2K]
H	Height of the fins [m]
Z	Height of fins at any point [m]
K	Thermal conductivity of air [W/m-K]
L	Length of solar air heater [m]
$\dot{m}$	Mass flow rate [kg /s]
Q	Heat transfer rate [W]
T_l	Air temperature [K]
T_{in}	Air inlet temperature [K]
T_{out}	Air outlet temperature [K]
T_p	Plate temperature [K]
R_e	Reynolds number
N_u	Nusselt number
P_r	Prandtl number
W	Duct width [m]
N	Number of fins
D_e	Equivalent diameter
P	Parameter of flow (Channel height × Width)
W_f	Width of fin

V	Velocity of air

Greek symbols

μ	Dynamic viscosity [Pa-s]
ρ	Density of air [kg/m^3]

Abbreviations

SAH	Solar Air Heater
FPC	Flat Plate Collector
TES	Thermal Energy Storage
PCM	Phase Change Material
CFD	Computational Fluid Dynamics
SHS	Sensible Heat Storage
LHS	Latent Heat Storage
DPSAH	Double Pass Solar Air Heater

Subscripts

in	Inlet
out	Outlet
f	Fin
l	Air
p	Plate

CHAPTER 1

INTRODUCTION

Energy demand kept on increasing in last few decades as world population increases and it becomes need of every one. Use of solar based application can help to manage the basic need of energy demand. Solar air heater (SAH) is one of the best applications of solar energy which utilize the solar radiation to heat the air for the purpose of drying the agriculture crops, fruits, nuts, and pre heat the air for industrial purpose mostly in textile industry. Use of Thermal energy heat storage systems with solar application have been gaining attention. These systems will have increasing importance for using solar energy in domestic and industrial heating system. As solar energy is a cyclic resource, storing excess energy for long or short-term periods will both increase the use of solar energy systems and decrease fossil fuel consumption. Power coming from the sun to earth is approximately 1.8×10^{11} MW, which is thousand times more than the consumption by the world for all energy based application. Thus solar energy can be used to supply enough amount energy for the future and present needs of the world so it is one of the most promising unconventional energy sources. [1]

One of the potential applications of solar energy is the supply of hot air for drying agricultural crops and heating buildings during winter. Due to the intermittent nature of solar energy, energy storage materials are used to store excess energy during the peak time of solar radiation to be used in off-sun hours or when the energy availability is inadequate. The storage materials improve the energy systems by smoothing the output and thus increasing reliability. Thermal energy can be stored as sensible heat, latent heat and chemical energy. Drying is a common technique for preservation of agricultural and other products, including fruits and vegetables. In developing countries, the traditional method of drying is by open air, which often results in food contamination and nutritional deterioration some of the problems associated with open-air drying can be solved through the use of solar dryers.[22]

Principle of solar air collector is to absorb heat from solar radiation coming through sun. The energy in the form of electromagnetic radiation from varying wavelengths (infrared to ultraviolet) can be termed as solar radiation, mainly it consist of an absorber plate, wooden box to support absorber plate, duct at the entry and exit for flow of fluid, transparent glass to cover, air blower and insulation in order to reduce heat losses. Absorber plate is blackened.

Transparent cover is use to minimize convective and radiative losses to the atmosphere. Heat is being transferred to air by flowing between the blackened absorber plate and transparent glass cover.

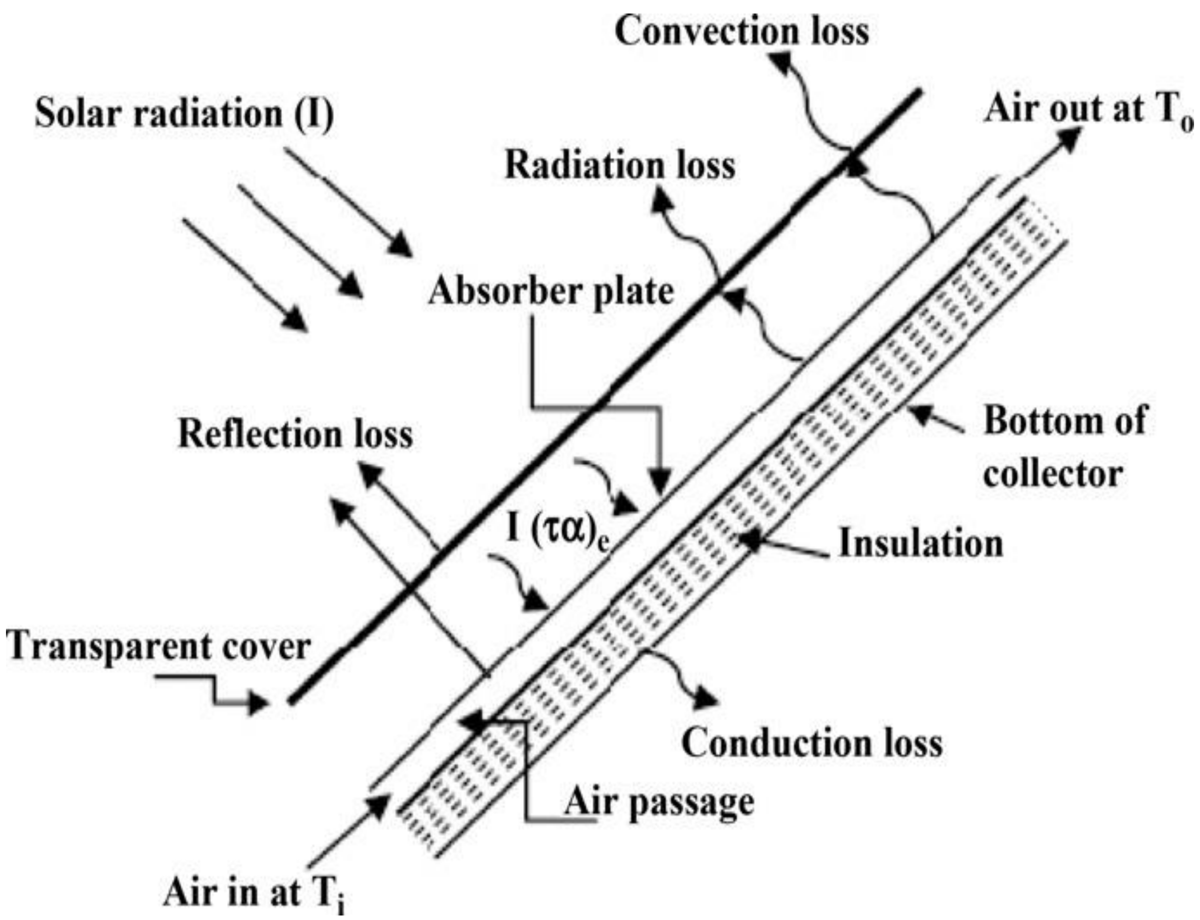

Fig. 1 Conventional Solar Air Heater [2]

1.1 History of Solar Air Heater:

Since 1700s, there were numerous inventions occurred in America to harness the sun's energy for heating home. E. Morse was the first American person who designed and produced solar air heater in1881.Its structure was simple like a wall hung timber framed cabinet made up from a black sheet of metal covered with a sheet of glass. It functioned purely by convection, facing the sun hot air would be emitted from the solar heated steel plate within the cabinet. This would rise and enter the building via an opening in the wall behind the cabinet. Hence little attention was given to this system. Solar heating systems have been in use for many years. Solar heat stored in iron was used in 1877 as reported by Daniels and

Duffie. The air blowing over the heated iron was then used to heat a home. The first accredited SAH was designed and produced by E.Morse (1881).The design deals with a simple wall hung wooden framed cabinet for a blackened metallic sheet covered with a transparent glass. It works purely on convection; the hot air would be emitted through a solar absorber made of steel with in the cabinet of the system. The system got a little attention, although variations were developed but were not known exactly. Several solar heated homes have been constructed and operated successfully over the past years. At present, this technology is referred as phase change materials (PCMs) and has numerous applications in industries, worldwide. Since that time, three more houses were built at MIT and research was continued up to 1978. The components used to be simple and reliable in operation and relatively easy to install by the home owner. In the past few years, many manufacturers of these components apparently recognized the trend to install to ward do-it-self solar heating system by its own, especially for building or space heating. [23]

Cabot in 1938 marked the beginning of modern research in solar heating at Massachusetts Institute of Technology (MIT). The SAHS was designed to carry approximately two-thirds of the total winter heating loads in Boston. Telkes and Baymond in 1949 defined a solar home at Dover (MIT) which utilized vertical southward SAHs and thermal energy storage (TES) in the heat of fusion of $NaSH_3$. The main objective to design this system was to carry the total heating loads (having theoretical capacity in its storage system to carry the desired heating load) at least for five days. Lateron, Bliss in 1955 has been developed and determined the performance of a fully solar heated house in the Arizona desert, through-flow of the air heater and a TES unit. Lof in1959 has designed some solar air heating systems over lapped transparent glass-plate type solar collector sand a pebble bed for TES and using these concepts to build a dwelling near Denver. The year round performance of this SAHs was investigated thoroughly and reported by Lof et al., in 1963, 1964, 1976, and 1978. Close et al. (1968) has described another SAHs used for limited heating of a laboratory cum building in Australia, which was operated for several years. This system used a 56 m^2 V-grove SAH and a packed bed storage (PBS) unit. Since 1970, different types of experimental systems for air heating are developed and their performance has been calculated and reported. After that, Weiss in 2003 had discussed the design n and optimization of many different European ‘solar combine system’. [3]

1.2 Component of solar air heaters:

SAHs consist of four major elements;

1. **Absorber plate** to absorb the solar radiation coming from the sun. It's blackened to absorb more solar radiation. Different modification can be done on absorber plate to improve the performance of SAH such as improved thermal conductivity of absorber plate, create artificial roughness on the surface of absorber plate and use of fins to increase the surface area of the SAHs.
2. **Transparent cover(s)** to allow solar energy to pass through and reduces convective losses and radiative heat loss from the absorber plate to surrounding
3. **Heat transport fluid** (the air) flowing through the duct which utilize heat from the absorber to absorb thermal energy to heat up.
4. **Heat insulating backing** to minimize the heat losses from the collector to the surrounding.

Fan or blower can be used to handle the large amount of air and heat storage medium can be use.

1.3 Models of solar air heaters:

Various models of solar air heater are:

1. **Solar air heater with or without thermal storage**
2. **Solar air heaters with concentrators**
3. **Hybrid solar air heaters**

1.3.1 Solar air heater with or without thermal storage: The thermal heat storages purposely for use solar thermal applications are;

(i) Sensible heat storage (SHS): As sensible heat in solids (rocks or water). The heat storage medium, thereby experiences an increase in temperature without undergoing a change in its phase

(ii) Latent heat storage (LHS): As latent heat of fusion in suitable chemical compounds (paraffin waxes and inorganic salts). By using these heat storing materials one cannot only improve the thermal performance of a SAH but extend the duration of heating up to long hours. Besides this, a good heat storing capacity of these materials is very useful for solar thermal system stopper for min poor ambient conditions or in the night.

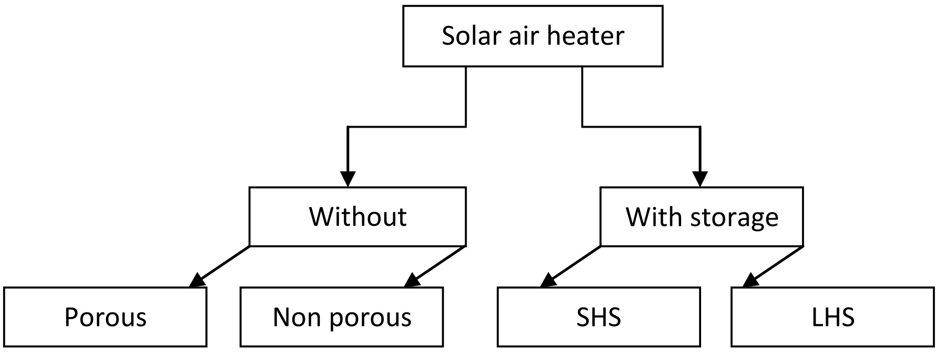

Fig 1.2 Classification of solar air heater

1.3.2 Solar air heaters with concentrators: Concentrating solar collectors (reflective and refractive) provide energy at temperatures higher than FPCs. They concentrate (re-direct also) solar radiation into the absorber and generally necessitate tracking of the sun.

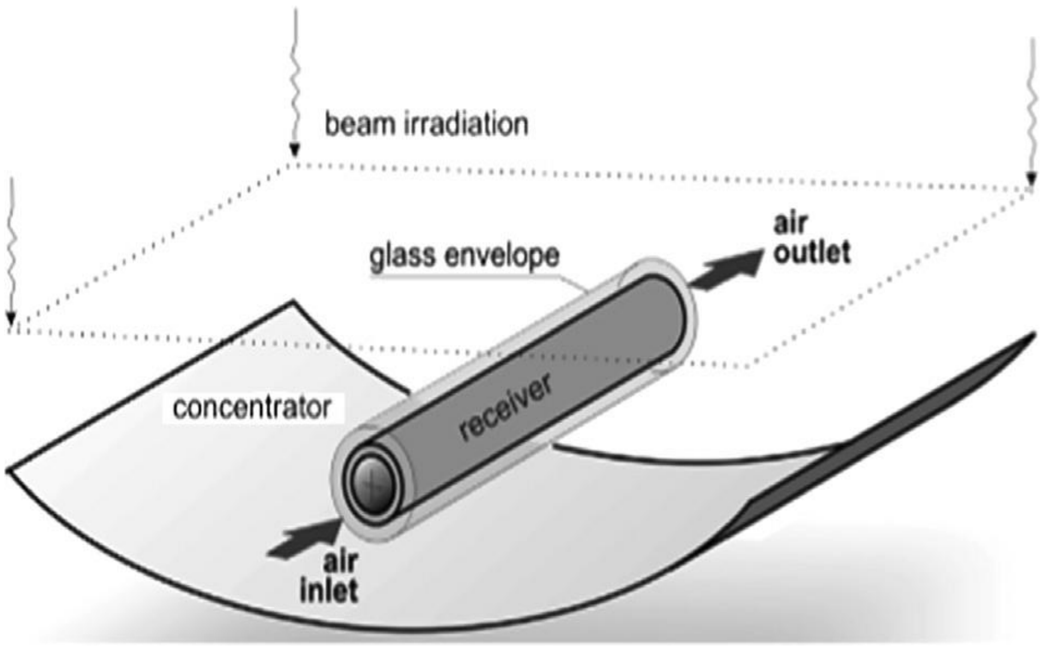

Fig.1.3 Concentrator solar air heater [4]

1.3.3 **Hybrid solar air heaters:** The most commonly used technologies for domestic hot water heating and space heating are a photovoltaic and a solar collector. Additional power backup has not only enhanced the efficiency of a solar thermal system, but also help the system to perform for a long hours in poor ambient conditions.

Fig 1.4 Hybrid Solar Air Heater [4]

1.4 Thermal energy storage:

Various researches have been done on the use of TES medium and now a days it mostly uses with Solar heat collector.TES systems can be very helpful in improving the performance of energy conversion equipment such as SAH. Thermal energy storage is divided into three categories;

1. **Sensible heat storage (SHS):-**Thermal energy is stored by increasing the temperature ofa liquid or solid, using the heat capacity and 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.
2. **Latent heat storage (LHS):-** Thermal energy is stored at the time of phase change from solid to liquid or liquid to vapor in the form of latent heat of fusion and vaporization respectively. LHS medium is gaining more attention because it stores more energy in the form of latent heat of fusion and vaporization. Paraffin wax is mostly used latent heat storage material because of its favorable properties.
3. **Thermochemical energy storage:-**Thermochemical systems rely on the energy absorbed and released in breaking and reforming molecular bonds in a completely reversible chemical reaction.

1.5 Need of performance analysis for Solar Air Heater:

The acceptance of solar energy technology depends on its efficiency, cost effectiveness, durability and reliability among other factors. Many solar thermal systems, such as solar water heaters, air heaters and distillation systems have improved in terms of efficiency and reliability.

A flat plate solar air heater differs from more conventional heat exchangers in several respects. The latter usually employ a fluid to exchange high heat transfer rates using conduction and convection. In solar air heaters, energy is transferred from a distant source of radiant energy directly into air. The heat may then be utilized by passing air through a conduit system located between the bottom and absorbing plate. The heated air is subsequently used for space heating and drying

1.6 Organization of Thesis

Chapter 1: Introduction

In this chapter the introduction of the solar air heater and different type of models of SAH, history of SAH, various applications, advantages and limitations of SAH system. Objectives of the study are also included.

Chapter 2: Literature Review

In this chapter overview of the available literatures corresponding to the Fin type SAH and use of thermal energy storage in SAH has been discussed. Observations are based on using this knowledge in the present study.

Chapter 3: Mathematical modeling of fin type Solar Air Heater

In this chapter heat transfer equation through fined surface has been used to stabilize a relation between fin height and no of fins. Before using these heat transfer equation same assumption were made like amount of heat to be transferred through fined surface, width of the fins, etc.

Chapter 4: Development of Solar air Heater

It includes the detail of complete experimental setup of fin type solar air heater and development of SAHs components. And also explain the use of that component in SAH.

Chapter 5: Experimental Setup

In this chapter arrangement of experimental setup has been discussed.

Chapter 6: Experimentation and Observations:

This chapter includes experimental procedure and detailed observation of 14 days.

Chapter 7: Results and discussion:

In this chapter sample calculation of single data from the observation has been presented. It also includes percentage improvement in the performance of SAH.

Chapter 8: Conclusions:

Conclusions of experimental results have been summarized in this chapter. Scope of future work has been added.

CHAPTER 2
LITERATURE REVIEW

A comprehensive literature review has been done on the performance analyses of solar air heater systems in this chapter. Number of researches is going on to develop improved design and also for improve in the performance of the SAH by integrating flat plate collector with energy storage systems. According to investigations around 20% of the world population today is undernourished. The increase in world population will strengthen the yet existing population food imbalance. Besides increasing food supply and limiting population growth, drastically reducing the food losses which occur throughout food production, harvest, post-harvest, and marketing seems to be a viable option. The reduction of food losses is particularly a problem for small farmers in developing countries who produce more than 80% of the food. Solar drying is in practice since time immemorial for preservation of food and agriculture crops. Solar dryers used in agriculture for food and crop drying are used for industrial drying processes. They can be proved to be a very useful device from the energy conservation point of view. It not only saves energy but also saves a lot of time, occupies less area, improves quality of the product, makes the process more efficient, and also protects the environment.

Agricultural products such as tobacco, tea, coffee, fruit, cocoa beans, rice, nuts, and timber generally require drying through a consistent application of relatively low heat. Traditionally, crop drying has been accomplished by use of fossil fuels and burning wood in ovens or open air drying under screened sunlight. These methods, however, have their shortcomings. The former is expensive and damages the environment and the latter is susceptible to the variety and unpredictability of the weather. Solar crop drying by use of SAH is a good option and it dries crops with more efficiency, uniformity, and less expense. A solar crop drying system does not solely depend on solar energy to function it combines fuel burning with the energy of the sun, thus reducing fossil fuel consumption. In this chapter various designs of SAH and its types and performance analysis are reviewed. Special attention is given to the solar drying technologies that facilitate drying of crops in off-sunshine hours.

This chapter has been divided into various categories for batter understanding.

2.1 Theoretical investigation:

V.V. Tyagi et al. [5] observed recent researches focused on heat storage medium, as latent heat storage is more efficient than sensible heat storage in order to improve the performance of SAH. Authors presented holistic view of available solar air heater for different applications and their performance. As per author it is very difficult task to classify SAH as there are numbers of configurations and many of which are empirical constructions. In this paper SAH classified on the basis of thermal storage material used.

S. VijayavenkataRaman et al. [6] presented comprehensive review of different solar drying technologies used for drying different material and crops. The various designs of SAH, its types and performance analysis are reviewed. Special attention is given to the solar drying technologies that facilitate drying of crops in off-sunshine hours. The solar dryers specifically designed or tested using specific crops like the vegetable dryer, fruit dryer, grain dryer, grape dryer, and so on are also reviewed with details about the specifications and the results. They concluded that best alternate to overcome the disadvantage of traditional open sun drying and the use of fossil fuels is the development of solar crop dryers. In addition to mitigation of fossil fuel use, the quality of the dried crops is also higher and the loss of dried products is considerably reduced. Various types of dryers like natural convection and forced convection dryers, direct and indirect type dryers, integral dryers, greenhouse dryers, cabinet dryers, tunnel dryers, mixed mode dryers were reviewed with respect to their design and performance.

Abhishek Saxena et al. [7] presented a comprehensive study at the current status of research concentration is mainly focused on the enhancement of heat transfer rate and efficiency. One such addition to the research scenario is the introduction of Granular carbon which is a long term heat absorbing media inside solar heater. The analysis of thermal performance has been done on different configuration by operating it on natural and forced convection. The primary aim of the experiment was to operate it economically by substituting the use of blower of higher power consumption. As the moving parts are absent, the operating cost and power consumption is decreased.

Abhishek Saxena et al. [8] observed by studying the literatures that all the elements of a solar air heater such as; an absorber tray, the ducts, glazing, insulation, extended surfaces, as well as the tilt angle , have a significant effect on the thermal performance of the system. They also explain the various methods that are used to improve the thermal performance of SAHs such as; optimizing the dimensions of the air heater construction elements, use of extended surfaces with different shapes and dimensions, use of sensible or latent storage media, use of concentrators to augment the available solar radiation, integrating photovoltaic elements with the heaters, etc., are also reported. Besides this, some benefits by using the SAHs has been discussed.

2.2 Numerical and Mathematical modeling:

Paisarn Naphon [9] studied numerically, develop mathematical model for double pass flat plate solar air heater with longitudinal fins that model described the heat transfer characteristics of the DPSAH derived from the conservation equations of energy. Performance of SAH is predicted at air flow rate ranging between 0.02 and 0.1 kg/s. He founded that the outlet air temperature rapidly decreases with increasing air mass flow rate and outlet temperature increases with increases in number of fins. It was also founded that the thermal efficiency increases with increasing the height and number of fins but entropy generation is inversely proportional to the height and number of fins.

P.T. Saravanakumar et al. [10] studied numerically for thermal performance of the flat plate solar air heaters with and without thermal storage are derived from energy equation. They employed implicit method of finite difference scheme to solve these models and also consider effect of thermal conductivity of thermal heat storage medium on the heat transfer characteristic and performance is considered. The results validated by comparison with experimental data.

2.3 Experimental investigation:

Many experimental work have been carried out on the solar air heater. In the experimental studies, researchers have revealed that performance of SAHs is getting affected by the mass flow rate of air, design of absorber plate, and artificial roughness parameters of absorber plate, intensity of solar radiation, and type of SAH etc.

A. Madhlopa and G. Ngwalo [11] in this experimental study, an indirect type natural convection solar air heater (solar dryer) integrated with solar collector storage and biomass backup heaters were developed. The absorber (plate) of the solar air heater was a horizontal concrete structure integrated to a rock bed. The backup heater was integrated to the solar collector and operated on wood shavings. The model was tested in three operation modes which were solar, biomass and solar-biomass by drying fresh pineapples outdoors under different weather conditions. Results show that the dryer is capable of reducing the moisture content of pineapple slices to acceptable levels, and retaining part of the vitamin C in the slices. The drying process is fastest in the solar-biomass mode of operation while the efficiency of the dryer is most satisfactory in the solar mode.

Peng et al. [21] carried out experiment study on single pass SAH having metal pin fin which are blackened and attached to the stainless steel sheet of 1 mm thickness and it was found that average efficiency of 25 kinds of pin fins array collector reached 50 - 74%.

Foued Chabane et al. [22] performed a experimental study over heat transfer and thermal performance with longitudinal fins of solar air heater. Five fins under the absorber plate (2m×1m) with a semi-cylindrical longitudinal form was 1.84 meter length and 0.03 meter radius and distance between each fins was 120 mm. Experiment were performed for two different mass flow rate of 0.012 kg/sec and 0.016 kg/sec. Efficiency of the SAH with fin was found to be higher than the SAH without fins.

G. Kalaiarasi et al. [12] carried out experimental energy and exergy analysis of a flat plate solar air heater with a new design of integrated sensible heat storage. It has a specially designed absorber plate made up of copper strips (copper tubes with extended copper fins on both sides), welded longitudinal to one another. This copper tubes structure used as an integrated absorber cum storage unit, where a high quality synthetic oil (Therminol-55) is filled in these copper tubes as a sensible heat storage (SHS) medium. To study the impact of this design of SAH and the sensible heat storage over the performance of the conventional SAH, the results were compared with the output of a conventional SAH of similar dimensions (area of absorber plate = 2×1 m^2). For the comparison of their performances, the experiments were conducted on both the SAHs at same location, simultaneously. It ensures similar testing conditions such as the amount of solar radiation received and surrounding environment of the experimental setup. Exergy analysis is a powerful thermodynamic tool and it helps in computing the actual output of a system, theoretically. It helps the researchers to optimize the system design to compensate the present and also the future needs. Experiments were conducted for two different mass flow rates (0.018 kg/s, and 0.026 kg/s). The results showed that the maximum energy and exergy efficiency obtained was in the range of 49.4-59.2% and 18.25-37.53% respectively, for the SAH with sensible storage at mass flow rate = 0.026 kg/s. For both the mass flow rates, the energy and exergy efficiencies of the SAH with SHS were higher compared to the SAH without SHS. The maximum energy and exergy efficiencies of the conventional SAH observed are 32.07% and 19.79% respectively for mass flow rate= 0.026 kg/s. Similarly, the recorded maximum energy and exergy efficiencies of the SAH with SHS for the same mass flow rate are 59.02% and 37.53% respectively.

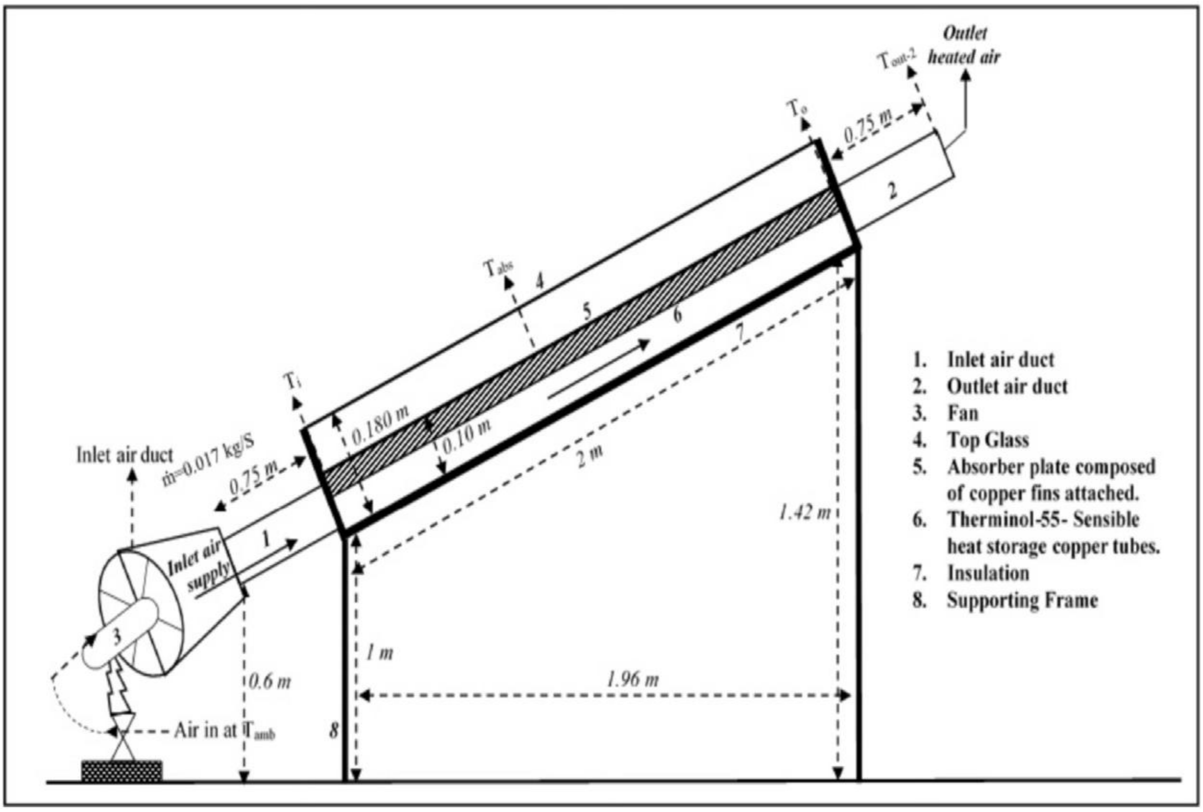

Fig. 2.1 schematic view of SAH with SHS

Foued Chabane et al. [13] experimentally investigated thermal performance of a single pass solar air heater with longitudinal fins attached. Two types of SAH of a same dimension were tested and their thermal performance was compared. The efficiency of the SAH depends significantly on the solar radiation and surface geometry. Longitudinal fins were used inferior to the absorber plate to increase the surface area for increase the heat transfer between the absorber plate and fluid (air) and the flow of fluid in the channel uniform. The effects of mass flow rate of air on the outlet temperature, the heat transfer in the thickness of the solar collector and thermal efficiency were studied. Experiments were performed for an air mass flow rate of 0.012 kg/s. Maximum efficiency was obtained by using five longitudinal fins as compare to without using fins. The maximum efficiency levels obtained for the 0.012 kg/s with and without fins were 40.02% and 34.92% respectively. A comparison of the results of the solar collector with and without fins shows that substantial enhancement in thermal efficiency of solar air heater.

Aymen EL Khadaoui et al. [14] carried out experiment on simple fabricated SAH with thermal heat storage, Paraffin wax (latent heat storage medium) is uses as a heat storage medium. Experimentation were performed on two similar designed SAH (with and without

Phase Change Material) and carried out to evaluate the PCM unit importance. Finding were, the daily energy efficiency of the SAH without PCM reached 17%, while the daily energy efficiency of the SAH with PCM reached 33%.

Omojaro and Aldabbagh [15] investigated the thermal performance of single pass and double pass solar air heater experimentally. Longitudinal fins were attached to steel wire mesh absorber plate. The effects of mass flow rate on the outlet temperature of fluid (air) and thermal efficiency have been studied. The efficiency of the heateris increased with increase in mass flow rate of air and for the same mass flow rate, double pass heater has higher efficiency than the single pass. The maximum efficiency of the double pass and single pass air heater is 63.58 % and 59.68 respectively for the mass flow rate of 0.038 kg/sec. The second analysis of work is using the wire mesh absorber plate which subsequently increases thermal performance of air heater as compared with the conventional air heater. The efficiency of the heater increases with increase in mass flow rate of air from 0.012 kg/sec to 0.038 kg/sec but ΔT decreases. The maximum air temperature difference obtained was 39.93˚C at the mass flow rate of 0.012 kg/sec.

Chii-Dong Ho et al. [16] designed and worked on double pass solar air integrated with fins and baffles and presented experimental as well as theoretical approaches. By the experiment they observed that the values deviate by 15% – 23% from that of theoretical predictions. The performance of different kinds of were compared. The main objective of the double pass heater to enlarging the heat transfer area. The collector efficiency of the fined with baffled double-pass with recycle design was found to be much higher than the other designs.

S.S. Krishnananth et al. [17] a double pass solar air heater integrated with thermal heat storage was designed and integrated. For this experiment they use Paraffin wax as a thermal heat storage medium. Comparative studies were conducted for performance analysis of SAH for different configurations. The efficiency of SAH used for experiment was found to be higher for SAH with heat storage than the SAH without thermal storage system and more heat gained by the air in case of heat storage medium. The conclusion made through this experiment will give the preference for SAH with thermal heat storage as compare to the SAH without heat storage.

2.4 Simulation based investigation:

Many studies have been conducted based of software simulation to evaluate the thermal performance of SAH to predict the result. It is a batter tool for us to find the different parameter to improve the performance of SAH that make over system to be cost effective.

Pavel Charvat et al. [18] carried out Simulations of the behavior of a solar air collector with integrated latent heat thermal storage were performed. The model of the collector was created with the use of coupling between TRNSYS 17 and MATLAB. Latent heat storage (Phase Change Material - PCM) was integrated with the solar absorber. The model of the latent heat storage absorber was created in MATLAB and the model of the solar air collector itself was created in TRNSYS with the use of TYPE 56. The simulations of two variants of the front and back pass solar air collector were carried out. The first variant was a collector with the light-weight solar absorber made of a simple metal sheet and the other variant was a collector with the absorber containing the phase change material. As expected, thermal storage in the form of the PCM led to lower air temperatures at the outlet of the collector during the day (during sunshine hours) and higher air temperatures after the sunset when the PCM was releasing the heat stored during the day. The simulations were carried out for the PCM with the melting temperature 40°C. More simulations are needed in order to investigate the influence of the melting temperature of the PCM, its thermal conductivity, total mass, etc. on the performance of the solar collector.

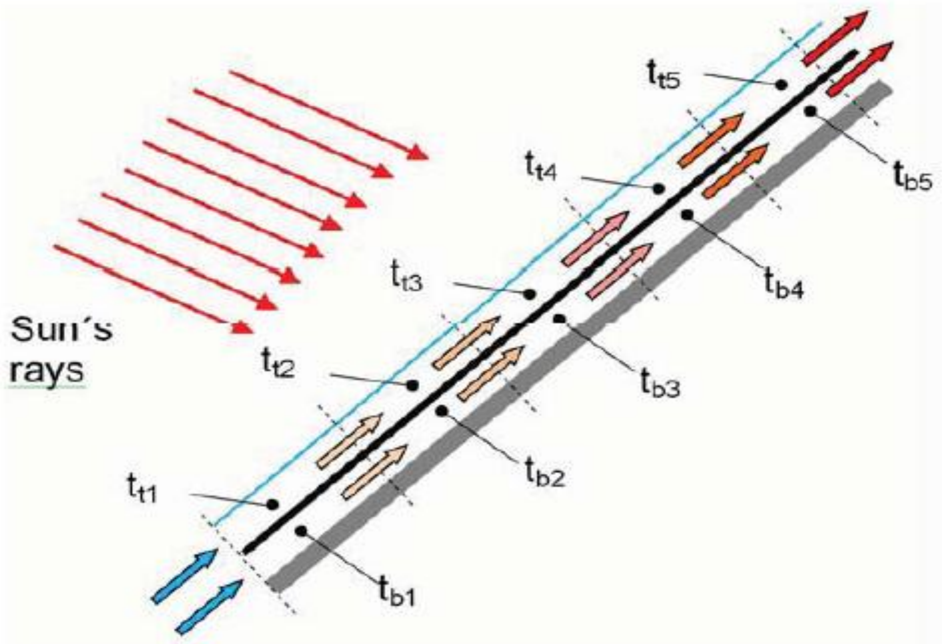

Fig 2.2 Model of the collector with the individual air-zones [18]

Wei Sun et al. [19] investigated by computational fluid dynamics (CFD) simulations in the design of SAH, channel depth is a principal variable to be fixed. Laminar model and k-ῳ turbulence model of Wilcox are used for the prediction of flow and temperature field in SAHs. Our study shows that the heat transfer corresponding to the temperature distribution across the channel in SAH varies greatly with the change of channel depth. Based on the first and second laws of thermodynamics, the optimal channel depths for type I and type II SAHs with black-painted absorber are suggested as 10 mm. It is found that with selective coating, the absorber plate should be further from the cover glazing in order to prevent excessive convective heat loss, the distance is better of no less than 20 mm.

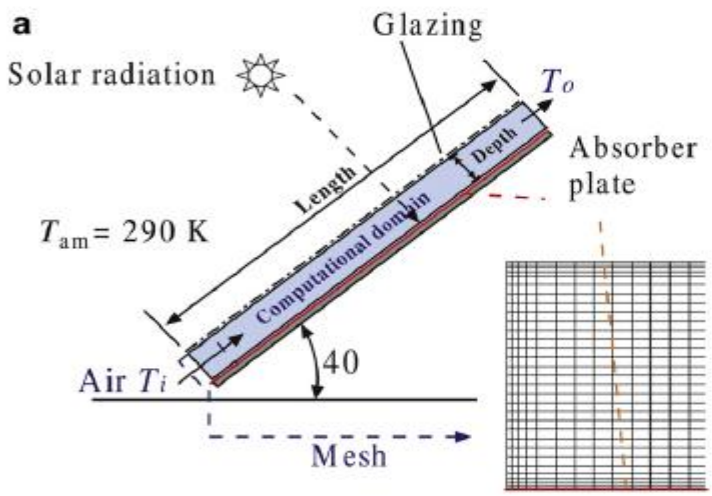

Fig 2.3 Schematics of computational modeling of solar air heater type I [19]

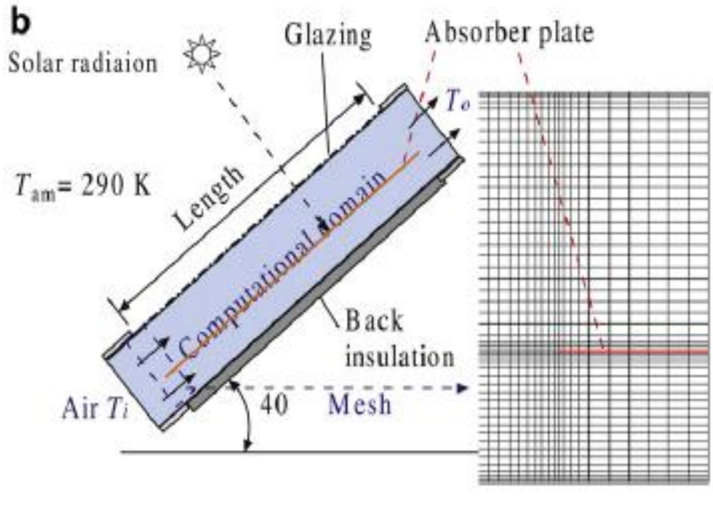

Fig 2.4 Schematics of computational modeling of solar air heater type II [19]

2.5 Observations based on the literature review:

A lot of researches have been done on the various designs and other parameter of SAH in last few decades. Various models have been developed based on the application with improved efficiency. Use of thermal heat storage of solar thermal system is a research area for many researchers in last few decades. Heat storage is divided in three type, sensible heat storage, latent heat storage and thermo-chemical heat storage, many LHS is most widely used due to large heat storage capacity. Performance of SAH depends upon various parameter like area of absorber plate, depth of solar air heater, no of glass cover, intensity of solar radiation, type of heat storage used, material of the absorber plate, thickness of the insulation, heat losses from the collector etc. now a day's software based work helps in to evaluate the performance of SAH in shorter time which is vary cost effective.

- Some commonly used thermal storage materials are the rock beds, pebbles beds, al composites, water and paraffin wax.
- Less researches on the Sensible storage materials mainly because it decomposes on high temperature.
- Same additives like Carbon fibers Expanded graphite, Graphite foams High thermal conductive particles are used to mix with paraffin wax to enhance thermal conductivity of paraffin wax that improve thermal performance of SAH.
- Longitudinal Fins are used to enhanced the heat transfer area and create air turbulence.
- Turbulence in air movement provides better heat transfer than laminar sub layer of air because of the higher momentum

2.6 Objectives of work:

A large number of researches are going on to improve the performance of the air heater as air has low heat absorbing capacity so development are going on the collector design to improve the performance. To improve the performance of SAH uses number of fins to increase the heat transfer area and artificial roughness on absorber plate.

1. Design and Development of Fin type SAH integrated with thermal heat storage.

2. To compare the performance of solar air heater with or without heat storage.

CHAPTER 3

MATHEMATICAL MODELLING OF FIN TYPE SOLAR AIR HEATER

Mathematical modeling has been done of fin type solar air heater for finding Fins height and number of Fins required for the purpose of heat transfer between the absorber plate and air. For mathematical modeling basic equations used to describe the heat transfer of the SAH.

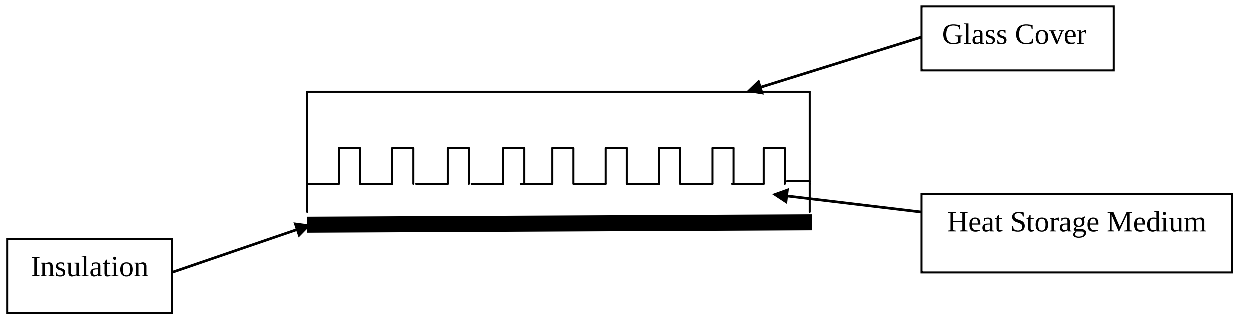

Fig 3.1 Cross-section view of SAH

Assumptions taken for mathematical modeling are as below:

- Flow of air is steady.
- Heat transfer coefficient is constant along the length of solar air heater.
- Thermal conductivity of fined absorber plate is constant .

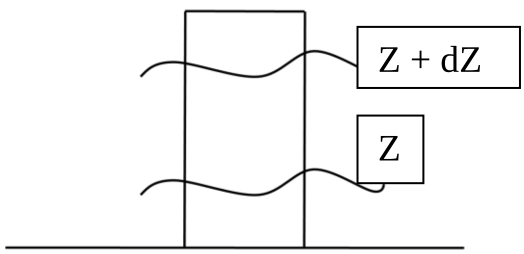

Fig 3.2 Cut section of single fin

Steady state heat transfer between air and the finned surface of absorber plate

Q_Z = $Q_{Z + dZ}$ = $2Lh(T-T_l)dZ$ 1

$Q_Z = - K_f A_f \, dT/dZ_{\text{at } z}$ 2

$Q_{Z+dZ} = -K_f A_f \, dT/dZ_{\text{ at } Z+dZ}$ 3

$-K_f A_f \, dT/dZ_{\text{ at } z} + (-K_f A_f (d^2T/dZ^2) \, dZ)$ 4

From eq^n 1,2 and 4

$K_f A_f (d^2T/dZ^2) = 2Lh(T-T_l)$

$d^2T/dZ^2 - 2Lh/K_f A_f (T-T_l) = 0$ 5

now $T-T_l = \theta$

differentiate eq^n 5

$dT/dZ = d\theta/dZ$ and $d^2T/dZ^2 = d^2\theta/dZ^2$

$d^2\theta/dZ^2 - (2Lh/K_f A_f)\theta = 0$ 6

putting $m = (2Lh/K_f A_f)^{1/2}$

were

L = Length of Solar Air Heater (m)

h = Convective heat transfer coefficient between plate and air(W/m^2K)

K_f = Thermal Conductivity of fin material (W/m-K)

A_f = Surface Area of fin ($L * W_f$)

dZ = Small portion of the height of fin

By solving above differential eq^n 6, we get

$\theta = C_1 \cosh m(H-Z) + C_2 \sinh m(H-Z)$ 7

C_1 and C_2 are constant, for find the value of these constant applying boundary condition for adiabatic tip,

at Z= 0 ; $\theta = T_p - T_l$ and at Z= H ; $d\theta/dZ = 0$

$\theta/\theta_0 = \cosh m(H-Z)/\cosh mH$ 8

$-K_f A_f \, dT/dZ_{\text{ at } Z=0} = (2K_f A_f L h_f)^{1/2} (T_p - T_l) \tanh mH$ 9

were

T_p = Temperature of absorber plate

T_l = Temperature of air

H = Height of the fin

The equation 9 represents the heat transfer from the single fin surface that is also equal to heat transfer through the convection so the equation 9 can be represent as follow.

$$\int_0^H 2hL(T - T_l)dZ = (\sqrt{2KhLA})(T_p - T_l)\tanh mH \qquad 10$$

Heat gain by the flowing air is summation of heat transfer through absorber plate, heat transfer through glass cover and air and heat transfer through finned surface. So that can be represent in the mathematical form as below.

$$Q = \dot{m}c_p(T_{out}-T_{in}) = Q_{ap} + Q_g + Q_{fin} \qquad 11$$

$$\dot{m}c_p(T_{out}-T_{in}) = hA_{frontal}(T_p-T_f) + N\int_0^H 2hL(T - T_l)dZ \qquad 12$$

By solving the equation10 and 12 we get;

$$Q = hA_{frontal}(T_p-T_l) + N\sqrt{(2K_f hLA_f})(T_p - T_l)\tanh mH \qquad 13$$

were

$A_{frontal}$ = Aperture area of SAH (1.25*0.8 m^2)

N = Number of fins

3.1 Relation between height of fins and number of fins:

There would be shading effect if height of the fins is more and if we increase number of fins then flow can be retarded so it is very important to find the relation between the height and the number of fins because these put impact on the performance of SAH.

To stabilize the relation between height and number of fins eq^n 10 is require and also require amount of heat that is transfer through fins.

It has been noticed that if we use fins that increase the performance of Solar air Heater by 10-15 % it means energy utilization increases by same percentage that is about 30-45 W.

Before solving eq^n 10 we need to find same parameter that has to constant to stabilize the relation.

Channel flow height = 15 cm

Width of the fins = 4 cm

Thermal conductivity of the material = 60-80 W/m-K

3.1.1 Convective heat transfer coefficient :

Considering the flow is a channel flow so equivalent diameter:

$$D_e = 4 * A / P = 0.2526 \text{ m}$$

Properties of air at 35 ^oC

K (Thermal conductivity) = 0.0275 W/m-K

Pr number = 0.699

ų (Dynamic viscosity) = 19.1308 $\times 10^{-6}$ Pa-sec

ρ (Density) = 1.12 Kg/m^3

$R_e = (\rho VD/ų)$

R_e= 44370.44 (Flow is laminar)

$N_u = 0.664(R_e)^{1/2} (P_r)^{1/3}$

$N_u = hD_e/K = 124.30$

$h = 2.75 \text{ W/m}^2\text{-K}$

Putting all the value inm = $(2Lh/ K_f A_f)^{1/2}$ = 1.31 m^{-1}

Form eq^n 10 = $N^* (2K_f hLA)^{1/2} (T_p - T_l) \tanh mH = 45$ W

T_p = 100^{o}C and T_l = 80 ^{o}C, now the equation would be converse into two variable which is number of fins and height of the fins

$$=N * \tanh mH = 0.41 \quad (14)$$

put N=5

$\tanh mH$ = 0.02823

H = 7.66 cm =8 cm

Now Put N=6

$\tanh mH$ = 0.06989

H = 5.78 cm = 6 cm

Dimensions of Fins were taken based on above calculated value and fins height and width were 6 cm and 4 cm respectively. Space between these fins was 8 cm.

CHAPTER 4

DEVELOPMENT OF SOLAR AIR HEATER

In the previous chapter relation between number and height of the fins has been stabilized and decided to develop a design which consist six fins of 6 cm height. In this chapter development of Solar Air Heater will be presented.

Solar air heater is type of flat plate collector that utilizes solar radiation to raise the temperature of flowing air. Solar radiation is absorbed by the absorber plate and air passes over the absorber plate by blower. Various researches have been done for improving the performance of SAH by changing various parameters like increasing surface area, by using multi pass design, high thermal conductivity materials for absorber plate, baffles and obstacles, nanoparticles mix with black paint, selective coating, heat storage materials, double glazing etc. To improve the performance of SAH some parameters have been used which are mentioned as below:

1. Increasing the surface area by means of integrating fins.
2. Use of thermal energy storage (TES).
3. Use of Iron dust with black paint to introduce Artificial roughness

4.1 Fabrication of solar air heater:

Performance enhancement is main motive of the work therefore developed a new design of fin type solar air heater is integrated with thermal energy storage. Components of SAH are listed as below:

1. Absorber plate cum thermal energy storage tank
2. Ducts at inlet and outlet
3. Glass cover
4. Insulation
5. Supporting stand for SAH
6. Blower
7. Thermal energy storage fluid

Absorber plate cum thermal energy storage tank made of 18 standard wire gauge of a galvanized iron sheet. Six numbers of fins are created on absorber plate and dimension of fins are 6 cm height and 4cm width. Fins are longitudinal. Plane sheet is converted into fined surface with the help of punching press by bending the plane iron sheet.

Fig 4.1 Finned absorber plate

After bending, its use to develop the structure like tank so that it can hold thermal energy storage fluid.

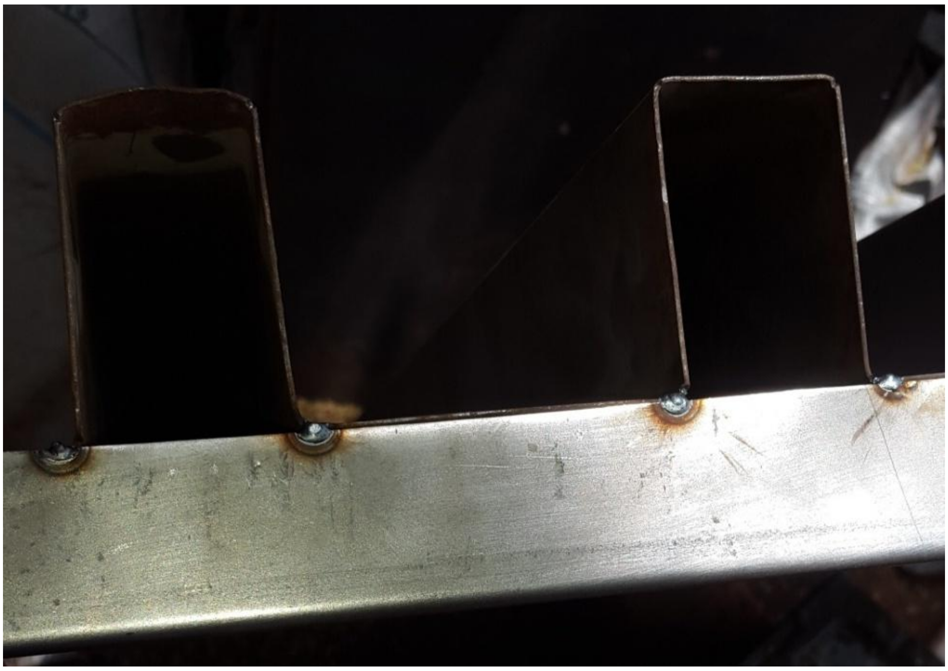

Fig 4.2 Absorber plate cum storage tank

Some other materials of high thermal conductivity can be used for absorber plate. But that has to be economic viable. Though Copper and Aluminum have high thermal conductivity, but due to high cost and low air heat transfer capacity, the use of these materials is not justified in SAHs.

For absorbing high amount of heat large amount of volume flow rate is require but therefore more external power would be require that increases the cost of overall setup and that will not justify the cost

Table 4.1 Thermal conductivity of various materials

Material	Thermal conductivity(W/m-K)
Aluminum	210
Brass	120
Bronze	27
Copper	390
Carbon Steel	60
Galvanized Iron	60-80

Specification of the finned absorber plate cum storage tank:

- Material : Galvanized Iron
- Thermal conductivity : 60-80 W/m-K
- Length : 125 cm
- Breath : 80 cm
- Thickness of Sheet : 18 standard wire gauge
- Selective coating : Black paint mixed with iron metal dust
- Capacity : 77.8 liter

Ducts and finned absorber plate cum storage tank made of same material. Ducts is directly welded to the absorber plate cum storage tank on both inlet and outlet side.

Specification of Duct:

Material : Galvanized iron sheet

Inlet pipe : MS

Inlet and Outlet Diameter : 5 cm

Fig. 4.3 Ducts Design

Complete assembly of absorber plate cum storage tank and ducts are supported by the wood. Wood is also act as the insulating material as it has low thermal conductivity. Still there is chance of heat loss so insulator is required. Same common insulating materials are: Thermocol, glass wool, rubber sheet, cotton etc. Thermocol is used to prevent the heat loss from bottom and side wall.

Table 4.2 List of Insulating materials [20]

S.No.	Name of material	Thermal conductivity at 200°C (W/m°C)	Density (kg/m³)	Out gassing	Saging	Colour change	Remarks
1.	Crown white wool	0.034	48	No	Yes	No	Good but expensive
2.	Crown bonded 150	0.066	48	Yes	No	Yes	Not good
3.	Spintex 300 industrial	0.975	48	No	No	No	Good, reasonable cost
4.	Glass wool	0.044	48	No	Yes	Yes	Good
5.	Calcium silicate	0.07	251.60	No	No	No	Good, but component system becomes very heavy
6.	Expanded polystyrene	0.017	32	Yes	No	Yes	Not good
7.	ISO Cyanurate	0.020	32	No	No	Yes	Under testing
8.	Phenotherm	0.029	32	Yes	No	Yes	Not good
9.	Thermocole	0.035	16	Yes	No	Yes	Not good
10.	Polyurethane foam	0.016	32	Yes	No	Yes	Not good
11.	Cellular foam	0.093	400	Yes	No	Yes	Not good
	PIPE SECTIONS						
12.	Rocklloyd	0.075	48	No	No	No	Good
13.	Isoloyd	0.021	32	No	No	No	Good
14.	Thermocole	0.035	16	No	No	No	Good
15.	Foam	0.017	32	No	No	No	Good

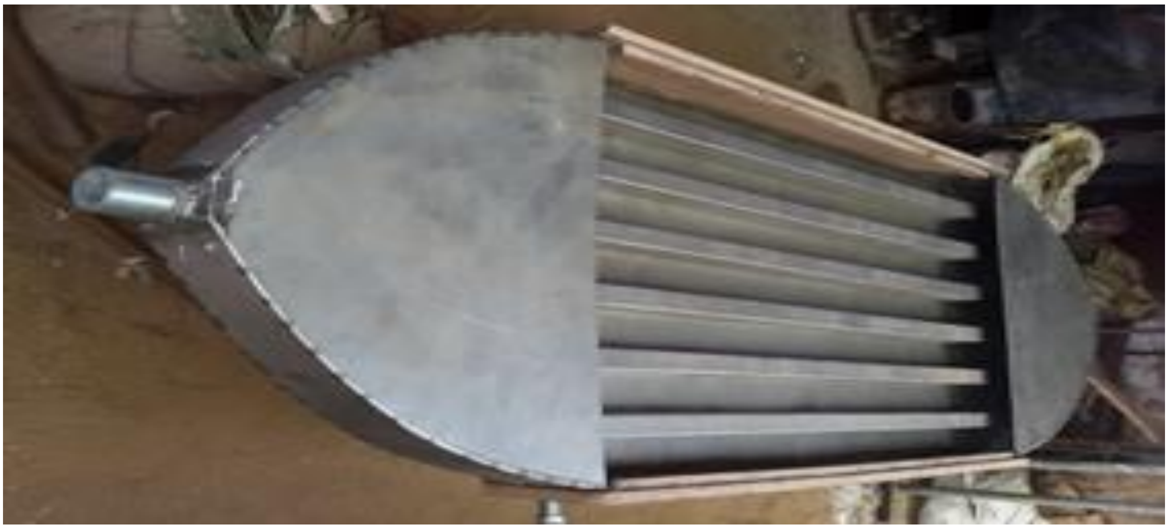

Fig 4.4 Assembly of ducts, absorber plate cum heat storage tank and insulation

Cover plate has an important characteristic through which solar radiation is transmitted. It is placed above the absorber plate. It should have strength, durability, non- degradability and high transmissivity. The function of cover plates are:

1. To transmit maximum solar energy to the absorber plate
2. To minimize upward heat loss from the absorber plate to the environment
3. To shield the absorber plate from direct exposure to weathering

Specification of Cover Plate

Material	: Glass
Transmissivity	: 80% Approximate
Length	: 140 cm
Width	: 85 cm
Thickness	: 5 cm

Heat transfer coefficient is low between the absorber plate and air for solar air heater. The heat transfer coefficient for a solar air heater can be increases by providing artificial roughness on the absorber plate because roughness increases friction between flowing air and absorber plate. For introduce roughness on the absorber plate Iron dust is mixed with the black paint to enhance the roughness of absorber plate. I introduce roughness to create turbulence and also increases contact area.

Fig 4.5 Roughness with black paint

Thermia S2 has been used for experiment. It is liquid SHS medium for store and deliver the energy when requires. It is high energy storage fluid. (Appendix-A)

Table 4.3 Various TES mediums

Medium	Material type	Temperature Range(^oC)	Density (Kg/m^3)	Specific Heat (J/Kg-K)
Rock	Solid	20	2560	879
Brick	Solid	20	1600	840
Concrete	Solid	20	1900-2300	880
Water	Liquid water	0-100	1000	4190
Ethanol	Organic	Up to 80	790	2400
Proponal	Organic	Up to 97	800	2500
Engine oil	Oil	Up to 160	888	1880
Octane	Organic	Up to126	704	2400
Isopentanol	Organic	Up tp 148	831	2200
Butanol	Organic	Up to 118	809	2400

Blower is use to handle the air flow above the absorber plate. External power is require to run the blower. Capacity of blower depends upon the size of the air heater and amount of air require to be handle.

Specification of blower:

Manufacturing company	:	Alpha
Voltage	:	220 V
Frequency	:	50/60 Hz
Power	:	600 W
Air deliver capacity	:	2.3 m^3/min
RPM	:	0-16000

Fig 4.6 Blower

CHAPTER 5

EXPERIMENTAL SETUP

Experimental setup is constructed and performed experimental investigation in Malaviya National Institute of Technology, Jaipur, India. The experiment was performed in summer season and experimental data has been collected for performance analysis of fin type SAH. Experimental setup is as shown below.

Fig 5.1 Experimental Setup

Experiment has performed for couple of week in two segments. 1^{st} segment is performed without heat storage and 2^{nd}segment is performed with heat storage fluid. These collectors are fixed facing south and kept inclined at an angle of 27^{o} with respect to the horizontal to maximize the solar radiation intensity falling on collector. Experiment was done for two different air outlet velocity i.e. 2.5 m/sec and 3 m/sec. Blower is used for handling the air flow over the finned absorber plate and blower is connected to the inlet through pipe. It can be operate at different velocities since it is variable flow device.

Calibrated copper-constantan thermocouple (T type thermocouple) is used for measurement of temperature. Three thermocouple wires are attached to the absorber plate at different location. Two thermocouple wires are attached at top and bottom side of the glass cover. Two thermocouple wires are dipped into the storage tank at different location. One each thermocouple wire is used at inlet and outlet of the SAH for measure inlet and outlet temperature of air. The intensity of solar radiation has been measured by using a solarimeter.

To improve the performance of fin type solar air heater, it is integrated with TES. Thermia S2 has been used as a heat storage medium in the liquid state.

Some measuring instruments are used for experiment. Which are listed as below.

1. Thermocouple wire
2. Digital Anemometer
3. Solarimeter
4. Digital Temperature Indicator

Fig 5.2 Digital anemometer

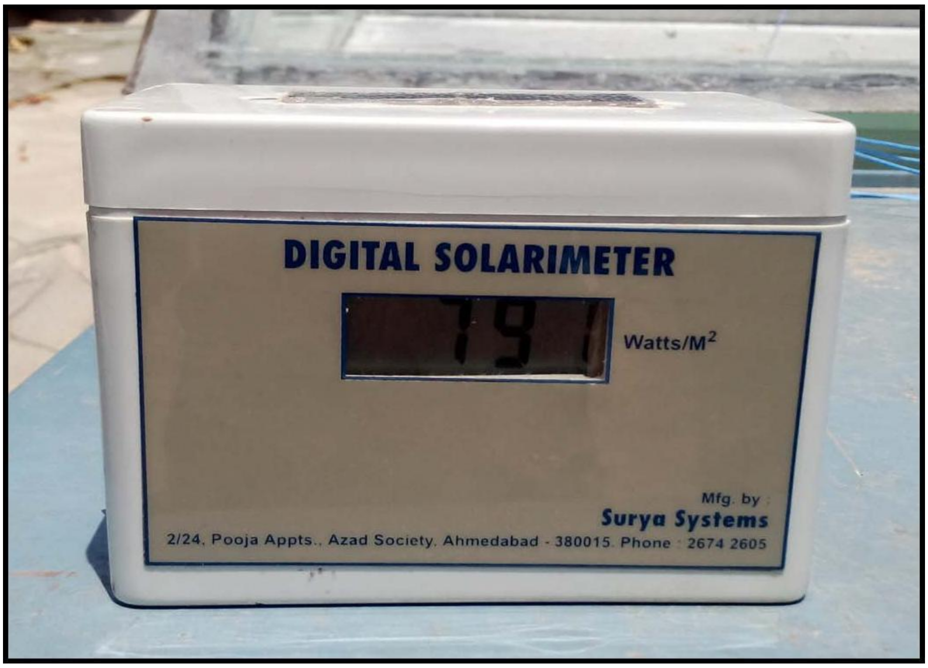

Fig. 5.3 Digital Solarimeter

Fig 5.4 Temperature indicator

CHAPTER 6

EXPEREMENTATION AND OBSERVATION

6.1 Experimentation:

Experimentation has been done on newly designed fin type solar air heater integrated with TES to find performance. Temperature has been measured by using T- type of thermocouple and temperature indicator at various points. Each reading has been noted at steady state condition means temperature of absorber plate became constant when air flow through SAH. Time interval between each reading was 45 minutes.

Reading has been note down for one complete day from 10:00 a.m. to 5:30 p.m. at constant time interval. Solar intensity has been measure through solarimeter by keeping it at same inclination angle as SAH.

Experiment Procedure:

- Before starting the experiment glass cover was cleaned properly.
- After starting the blower, the values of inlet air temperature and air velocity was noted down.
- After above step waited for same time till steady state point reached. Steady state point is point at which temperature of absorber plate become constant. Air outlet temperature, absorber plate temperature, glass temperature, temperature of heat storage fluid and air outlet temperature has been noted when steady state condition achieved.
- Switched to higher air velocity and wait till Steady state point and note down all required temperature.
- Same procedure followed for remaining readings.

6.2 Observations:

Total 14 sets of reading were done from 11 May 2017 to 5 June 2017. For better understanding, all the set of readings were created into tabular format. Amount of heat gain by the air is added in the table.

11 may to 19 may experiment performed without TES and 25 May to 5 June experiment performed with TES

Table 6.1 Readings for Thermal performance without TES 11-May-2017

Time	Plate temperature (°C)			Average Plate Temp (°C)	Glass Temperature (°C)		Air Temperature (°C)		Solar radiation (W/m²)	Air velocity (m/s)	Density Kg/m³	Specific Heat J/Kg-K	Mass Flow Rate Kg/s	Heat Gain Watt
	1	2	3		1	2	IN	OUT						
10:00	83	77	87	82.33	77	69	30	71	605	2.5	1.076	1007	0.00529	218.24
	79	75	81	78.33	73	67	30	69	605	3	1.079	1007	0.00636	249.80
10:45	85	77	88	83.33	77	70	31	73	628	2.5	1.071	1007	0.00526	222.52
	83	76	86	81.67	76	69	31	70	628	3	1.076	1007	0.00634	249.11
11:30	90	82	92	88.00	82	75	31	79	779	2.5	1.062	1008	0.00522	252.42
	85	78	89	84.00	80	74	31	75	779	3	1.068	1008	0.00630	279.23
12:15	96	87	97	93.33	83	77	32	84	803	2.5	1.053	1009	0.00517	271.41
	89	81	93	87.67	82	75	32	80	803	3	1.059	1008	0.00624	302.05
1:00	101	89	105	98.33	82	74	33	85	837	2.5	1.049	1009	0.00515	270.38
	94	83	97	91.33	81	73	33	80	837	3	1.057	1008	0.00623	295.20
1:45	98	85	98	93.67	81	74	34	83	702	2.5	1.051	1009	0.00516	255.27
	91	82	92	88.33	81	73	34	79	702	3	1.057	1008	0.00623	282.64
2:30	95	82	95	90.67	78	72	34	78	600	2.5	1.059	1008	0.00520	230.73
	91	80	92	87.67	76	70	34	74	600	3	1.065	1008	0.00628	253.14
3:15	87	78	92	85.67	74	67	32	69	490	2.5	1.076	1007	0.00529	196.95
	82	78	89	83.00	71	65	32	65	490	3	1.083	1007	0.00638	212.16
4:00	81	71	82	78.00	71	63	31	61	371	2.5	1.092	1006	0.00536	161.90
	79	70	80	76.33	68	60	31	58	371	3	1.097	1006	0.00647	175.65
4:45	74	69	75	72.67	63	55	30	53	291	2.5	1.108	1005	0.00544	125.82
	71	64	71	68.67	61	53	30	51	291	3	1.112	1005	0.00656	138.35
5:30	67	61	64	64.00	55	49	29	47	159	2.5	1.121	1005	0.00551	99.62
	61	58	62	60.33	51	45	29	43	159	3	1.128	1005	0.00665	93.56

Table 6.2 Readings for Thermal performance without TES 12-May-2017

Time	Plate temperature (°C)			Avearge Plate Temp (°C)	Glass Temperature (°C)		Air Temperature (°C)		Solar radiation (W/m^2)	Air velocity (m/s)	Density Kg/m^3	Specific Heat J/kg-k	Mass Flow Rate Kg/s	Heat Gain Watt
	1	2	3		1	2	IN	OUT						
10:00	79	72	81	77.33	74	67	30	68	539	2.5	1.081	1007	0.00531	203.21
	74	68	76	72.67	70	61	30	62	539	3	1.092	1006	0.00644	207.23
10:45	85	79	86	83.33	76	68	30	69	612	2.5	1.079	1007	0.00530	208.17
	82	75	83	80.00	72	64	30	66	612	3	1.085	1007	0.00640	231.87
11:30	93	85	94	90.67	87	79	31	78	791	2.5	1.063	1008	0.00522	247.40
	90	83	91	88.00	86	77	31	76	791	3	1.067	1008	0.00629	285.31
12:15	97	89	98	94.67	88	79	32	85	821	2.5	1.051	1009	0.00516	276.10
	91	88	93	90.67	86	76	32	82	821	3	1.056	1008	0.00623	313.75
1:00	103	91	106	100.00	88	79	34	87	849	2.5	1.045	1009	0.00513	274.53
	98	89	99	95.33	87	77	34	83	849	3	1.051	1009	0.00620	306.32
1:45	98	90	101	96.33	86	78	34	83	724	2.5	1.051	1009	0.00516	255.27
	94	88	95	92.33	82	75	34	80	724	3	1.056	1008	0.00623	288.65
2:30	94	82	94	90.00	80	74	35	79	629	2.5	1.056	1008	0.00519	230.08
	90	80	92	87.33	78	71	35	74	629	3	1.063	1008	0.00627	246.34
3:15	89	80	90	86.33	77	72	33	75	510	2.5	1.065	1008	0.00523	221.49
	85	78	85	82.67	75	70	33	70	510	3	1.073	1007	0.00633	235.68
4:00	84	78	86	82.67	71	64	31	69	390	2.5	1.078	1007	0.00530	202.64
	81	76	82	79.67	68	62	31	64	390	3	1.087	1007	0.00641	212.94
4:45	79	71	81	77.00	65	58	31	61	291	2.5	1.092	1006	0.00536	161.90
	74	69	75	72.67	63	55	31	59	291	3	1.096	1006	0.00646	181.99
5:30	70	63	71	68.00	59	50	30	54	167	2.5	1.106	1005	0.00543	131.05
	66	59	67	64.00	54	49	30	49	167	3	1.115	1005	0.00657	125.51

Table 6.3 Readings for Thermal performance without TES 15-May-2017

Time	Plate temperature (°C)			Average Plate Temp (°C)	Glass Temperature (°C)		Air Temperature (°C)		Solar radiation (W/m^2)	Air velocity (m/s)	Density (Kg/m^3)	Specific Heat (J/Kg-K)	Mass Flow Rate (Kg/s)	Heat Gain (Watt)
	1	2	3		1	2	IN	OUT						
10:00	79	72	82	77.67	65	59	30	68	490	2.5	1.081	1007	0.00531	203.21
	74	70	79	74.33	64	57	30	62	490	3	1.092	1006	0.00644	207.23
10:45	82	75	87	81.33	74	62	30	69	525	2.5	1.079	1007	0.00530	208.17
	78	72	83	77.67	73	60	30	66	525	3	1.085	1007	0.00640	231.87
11:30	91	81	92	88.00	80	79	31	78	705	2.5	1.063	1008	0.00522	247.40
	87	79	89	85.00	79	77	31	76	705	3	1.067	1008	0.00629	285.31
12:15	97	90	99	95.33	90	79	32	85	791	2.5	1.051	1009	0.00516	276.10
	94	88	96	92.67	90	76	32	82	791	3	1.056	1008	0.00623	313.75
1:00	109	97	109	105.00	88	79	34	87	817	2.5	1.045	1009	0.00513	274.53
	96	90	99	95.00	87	77	34	83	817	3	1.051	1009	0.00620	306.32
1:45	101	92	102	98.33	87	78	34	83	692	2.5	1.051	1009	0.00516	255.27
	92	86	94	90.67	82	75	34	80	692	3	1.056	1008	0.00623	288.65
2:30	95	83	96	91.33	79	74	35	79	597	2.5	1.056	1008	0.00519	230.08
	88	79	90	85.67	76	71	35	74	597	3	1.063	1008	0.00627	246.34
3:15	89	82	92	87.67	77	72	33	75	482	2.5	1.065	1008	0.00523	221.49
	84	78	84	82.00	71	70	33	70	482	3	1.073	1007	0.00633	235.68
4:00	82	75	83	80.00	69	64	31	69	353	2.5	1.078	1007	0.00530	202.64
	79	71	81	77.00	66	62	31	64	353	3	1.087	1007	0.00641	212.94
4:45	77	69	79	75.00	64	58	31	60	254	2.5	1.092	1006	0.00536	156.50
	72	68	73	71.00	63	55	31	59	254	3	1.096	1006	0.00646	181.99
5:30	71	67	71	69.67	58	50	30	53	178	2.5	1.106	1005	0.00543	125.59
	66	60	68	64.67	56	49	30	48	178	3	1.115	1005	0.00657	118.90

Table 6.4 Readings for Thermal performance without TES 16-May-2017

Time	Plate temperature (°C)			Average Plate Temp (°C)	Glass Temperature (°C)		Air Temperature (°C)		Solar radiation (W/m^2)	Air velocity (m/s)	Density Kg/m^3	Specific Heat J/Kg-K	Mass Flow Rate Kg/Sec	Heat Gain Watt
	1	2	3		1	2	IN	OUT						
10:00	82	77	86	81.67	76	68	30	70	571	2.5	1.078	1007	0.00530	213.31
	79	75	80	78.00	72	66	30	69	571	3	1.079	1007	0.00636	249.80
10:45	86	79	89	84.67	78	71	31	73	618	2.5	1.071	1007	0.00526	222.52
	84	77	86	82.33	75	69	31	71	618	3	1.074	1007	0.00633	255.02
11:30	92	83	91	88.67	83	76	31	79	762	2.5	1.062	1008	0.00522	252.42
	86	79	88	84.33	81	73	31	76	762	3	1.067	1008	0.00629	285.31
12:15	95	89	97	93.67	83	77	33	85	800	2.5	1.049	1009	0.00515	270.38
	90	82	94	88.67	83	75	33	82	800	3	1.054	1009	0.00621	307.19
1:00	103	92	107	100.67	85	78	34	87	823	2.5	1.045	1009	0.00513	274.53
	97	90	99	95.33	85	75	34	84	823	3	1.049	1009	0.00618	311.98
1:45	98	86	99	94.33	81	74	35	83	683	2.5	1.049	1009	0.00515	249.58
	92	84	94	90.00	81	73	35	80	683	3	1.054	1009	0.00621	282.12
2:30	95	85	94	91.33	78	71	33	79	591	2.5	1.059	1008	0.00520	241.22
	92	83	92	89.00	78	70	33	77	591	3	1.062	1008	0.00626	277.67
3:15	86	79	89	84.67	74	66	32	70	477	2.5	1.074	1007	0.00528	201.89
	83	76	86	81.67	72	65	32	68	477	3	1.078	1007	0.00635	230.37
4:00	80	72	82	78.00	71	63	31	61	365	2.5	1.092	1006	0.00536	161.90
	79	70	80	76.33	67	61	31	58	365	3	1.097	1006	0.00647	175.65
4:45	75	69	77	73.67	66	57	31	57	271	2.5	1.099	1006	0.00540	141.21
	72	64	74	70.00	64	54	31	55	271	3	1.103	1006	0.00650	156.99
5:30	68	62	63	64.33	56	52	30	53	185	2.5	1.108	1005	0.00544	125.82
	63	59	62	61.33	52	50	30	51	185	3	1.112	1005	0.00656	138.35

Table 6.5 Readings for Thermal performance without TES 17-May-2017

Time	Plate temperature (°C)			Average Plate Temp (°C)	Glass Temperature (°C)		Air Temperature (°C)		Solar radiation (W/m²)	Air velocity (m/s)	Density Kg/m³	Specific Heat J/Kg-K	Mass Flow Rate Kg/s	Heat Gain Watt
	1	2	3		1	2	IN	OUT						
10:00	84	78	88	83.33	78	70	30	72	614	2.5	1.074	1007	0.00528	223.14
	82	76	82	80.00	74	68	30	70	614	3	1.078	1007	0.00635	255.97
10:45	87	80	90	85.67	79	72	31	75	637	2.5	1.068	1008	0.00525	232.69
	85	78	88	83.67	77	71	31	73	637	3	1.071	1007	0.00631	267.03
11:30	91	82	94	89.00	82	76	33	79	792	2.5	1.059	1008	0.00520	241.22
	89	80	92	87.00	81	74	33	75	792	3	1.065	1008	0.00628	265.79
12:15	96	89	98	94.33	84	78	37	84	827	2.5	1.045	1009	0.00513	243.45
	90	83	94	89.00	82	77	37	80	827	3	1.051	1009	0.00620	268.81
1:00	102	92	108	100.67	86	79	38	88	847	2.5	1.037	1010	0.00509	257.26
	100	91	103	98.00	85	77	38	85	847	3	1.042	1009	0.00614	291.30
1:45	99	89	101	96.33	81	74	37	85	723	2.5	1.043	1009	0.00512	248.15
	96	86	97	93.00	81	73	37	81	723	3	1.049	1009	0.00618	274.54
2:30	95	82	95	90.67	78	72	36	80	611	2.5	1.053	1009	0.00517	229.65
	91	80	92	87.67	76	70	36	79	611	3	1.054	1009	0.00621	269.58
3:15	89	79	92	86.67	74	68	35	72	502	2.5	1.067	1008	0.00524	195.49
	86	78	90	84.67	71	67	35	70	502	3	1.07	1008	0.00631	222.53
4:00	82	71	83	78.67	71	63	34	65	393	2.5	1.079	1007	0.00530	165.47
	79	70	80	76.33	68	60	34	64	393	3	1.081	1007	0.00637	192.51
4:45	74	69	75	72.67	64	55	33	59	318	2.5	1.094	1006	0.00537	140.57
	71	64	71	68.67	63	53	33	57	318	3	1.097	1006	0.00647	156.13
5:30	65	60	67	64.00	61	56	32	55	192	2.5	1.103	1006	0.00542	125.37
	61	58	64	61.00	60	55	32	53	192	3	1.106	1005	0.00652	137.60

Table 6.6 Readings for Thermal performance without TES 18-May-2017

Time	Plate temperature (°C)			Average Plate Temp (°C)	Glass Temperature (°C)		Air Temperature (°C)		Solar radiation (W/m²)	Air velocity (m/s)	Density Kg/m³	Specific Heat J/Kg-K	Mass Flow Rate Kg/s	Heat Gain watt
	1	2	3		1	2	IN	OUT						
10:00	81	74	83	79.33	73	68	30	69	502	2.5	1.079	1007	0.0053	208.17
	79	73	81	77.67	72	67	30	66	502	3	1.086	1007	0.0064	232.08
10:45	86	80	88	84.67	77	71	31	73	561	2.5	1.071	1007	0.0053	222.52
	85	79	87	83.67	76	70	31	71	561	3	1.074	1007	0.0063	255.02
11:30	91	82	94	89.00	82	76	33	78	741	2.5	1.06	1008	0.0052	236.20
	89	80	92	87.00	81	74	33	76	741	3	1.063	1008	0.0063	271.61
12:15	95	89	97	93.67	84	79	37	83	804	2.5	1.046	1009	0.0051	238.50
	93	83	95	90.33	82	77	37	81	804	3	1.048	1009	0.0062	274.28
1:00	102	93	106	100.33	87	80	37	87	821	2.5	1.04	1009	0.0051	257.75
	100	92	102	98.00	86	79	37	85	821	3	1.043	1009	0.0061	297.78
1:45	98	90	101	96.33	89	74	36	85	692	2.5	1.045	1009	0.0051	253.81
	97	89	98	94.67	88	73	36	81	692	3	1.051	1009	0.0062	281.31
2:30	95	84	96	91.67	81	71	35	81	604	2.5	1.053	1009	0.0052	240.09
	91	82	92	88.33	80	70	35	79	604	3	1.056	1008	0.0062	276.10
3:15	90	80	92	87.33	74	67	35	73	489	2.5	1.065	1008	0.0052	200.40
	88	79	91	86.00	71	65	35	72	489	3	1.067	1008	0.0063	234.59
4:00	83	73	83	79.67	71	65	34	67	383	2.5	1.076	1007	0.0053	175.65
	81	71	80	77.33	69	63	34	66	383	3	1.078	1007	0.0064	204.78
4:45	74	69	74	72.33	66	54	32	59	301	2.5	1.094	1006	0.0054	145.98
	71	64	71	68.67	63	53	32	57	301	3	1.097	1006	0.0065	162.64
5:30	66	60	67	64.33	61	56	31	56	197	2.5	1.101	1006	0.0054	136.03
	62	58	65	61.67	60	55	31	53	197	3	1.106	1005	0.0065	144.15

Table 6.7 Readings for Thermal performance without TES 19-May-2017

Time	Plate temperature			Average Plate Temp	Glass Temperature		Air Temperature (°C)		Solar radiation (W/m²)	Air velocity	Density	Specific Heat	Mass Flow Rate	Heat Gain
	(°C)			(°C)	(°C)					(m/s)	Kg/m³	J/Kg-K	Kg/s	Watt
	1	2	3		1	2	IN	OUT						
10:00	82	75	84	80.33	71	66	30	69	536	2.5	1.079	1007	0.00530	208.17
	80	74	82	78.67	70	63	30	67	536	3	1.083	1007	0.00638	237.87
10:45	86	82	89	85.67	76	71	31	73	659	2.5	1.071	1007	0.00526	222.52
	85	79	87	83.67	74	69	31	71	659	3	1.074	1007	0.00633	255.02
11:30	91	82	94	89.00	82	75	33	77	718	2.5	1.062	1008	0.00522	231.39
	89	80	92	87.00	81	74	33	74	718	3	1.067	1008	0.00629	259.95
12:15	95	89	97	93.67	84	79	37	83	758	2.5	1.046	1009	0.00514	238.50
	93	83	95	90.33	83	77	37	81	758	3	1.049	1009	0.00618	274.54
1:00	101	93	105	99.67	87	81	37	86	810	2.5	1.042	1009	0.00512	253.08
	99	92	103	98.00	86	79	37	83	810	3	1.046	1009	0.00617	286.20
1:45	96	89	100	95.00	89	74	36	83	712	2.5	1.048	1009	0.00515	244.15
	95	88	98	93.67	88	73	36	81	712	3	1.051	1009	0.00620	281.31
2:30	93	85	96	91.33	83	70	35	80	645	2.5	1.054	1009	0.00518	235.10
	90	81	91	87.33	81	69	35	78	645	3	1.057	1008	0.00623	270.08
3:15	90	80	92	87.33	74	66	35	75	508	2.5	1.062	1008	0.00522	210.35
	88	79	91	86.00	72	65	35	73	508	3	1.065	1008	0.00628	240.48
4:00	83	74	83	80.00	71	62	34	68	413	2.5	1.074	1007	0.00528	180.64
	81	72	80	77.67	69	61	34	65	413	3	1.079	1007	0.00636	198.56
4:45	76	69	74	73.00	67	59	32	59	314	2.5	1.094	1006	0.00537	145.98
	73	66	72	70.33	65	58	32	57	314	3	1.097	1006	0.00647	162.64
5:30	68	61	69	66.00	62	57	31	56	221	2.5	1.101	1006	0.00541	136.03
	64	59	67	63.33	61	56	31	54	221	3	1.105	1005	0.00651	150.57

Table 6.8 Readings for Thermal performance with TES 25-May-2017

Time	Plate temperature			Average plate temp	Glass Temperature		TES temperature (^oC)		Air Temperature		Solar radiation	Air velocity	Density	Specific Heat	Mass Flow Rate	Heat gain
	(^oC)			(^0C)	(^oC)				(^oC)		(W/m^2)	(m/s)	Kg/m^3	J/Kg-K	Kg/Sec	Watt
	1	2	3		1	2	1	2	IN	OUT						
10:00	54	52	57	54.33	55	52	49	53	29	52	491	2.5	1.126	1005	0.00551	127.48
	53	51	56	53.33	55	51	49	53	29	49	491	3	1.126	1005	0.00662	133.02
10:45	60	56	62	59.33	60	56	52	60	30	54	558	2.5	1.126	1005	0.00551	133.02
	59	55	60	58.00	60	55	52	60	30	52	558	3	1.126	1005	0.00662	146.32
11:30	68	65	72	68.33	67	61	58	70	32	58	642	2.5	1.126	1006	0.00551	144.25
	66	64	70	66.67	67	60	58	71	32	55	642	3	1.126	1005	0.00662	152.97
12:15	79	72	84	78.33	73	69	69	82	36	66	700	2.5	1.126	1007	0.00551	166.61
	77	70	81	76.00	72	68	69	83	36	62	700	3	1.126	1007	0.00662	173.27
1:00	83	76	88	82.33	79	71	71	87	38	71	688	2.5	1.126	1008	0.00551	183.45
	81	75	85	80.33	77	70	71	88	38	68	688	3	1.126	1008	0.00662	200.13
1:45	90	79	92	87.00	76	70	72	91	39	76	639	2.5	1.126	1009	0.00551	205.89
	88	77	91	85.33	76	67	72	91	39	74	639	3	1.126	1009	0.00662	233.71
2:30	90	86	94	90.00	76	73	74	97	37	79	603	2.5	1.126	1009	0.00551	233.71
	89	80	91	86.67	76	72	75	97	37	76	603	3	1.126	1009	0.00662	260.42
3:15	86	81	90	85.67	74	69	72	92	36	76	470	2.5	1.126	1008	0.00551	222.36
	82	79	87	82.67	74	68	71	92	36	74	470	3	1.126	1008	0.00662	253.49
4:00	81	72	83	78.67	69	63	70	89	36	72	391	2.5	1.126	1008	0.00551	200.13
	78	70	80	76.00	68	64	70	89	36	69	391	3	1.126	1007	0.00662	219.92
4:45	73	68	75	72.00	60	55	65	84	35	66	271	2.5	1.126	1007	0.00551	172.16
	71	64	73	69.33	60	54	64	84	34	64	271	3	1.126	1007	0.00662	199.93
5:30	70	66	71	69.00	59	55	63	79	31	63	193	2.5	1.126	1006	0.00551	177.54
	69	64	69	67.33	59	54	62	79	31	60	193	3	1.126	1006	0.00662	193.07
6:00	61	58	66	61.67	56	51	60	77	30	59	108	2.5	1.126	1006	0.00551	160.89
	60	56	65	60.33	55	50	60	77	30	57	108	3	1.126	1006	0.00662	179.76
6:30	58	54	60	57.33	51	48	58	71	30	56	44	2.5	1.126	1005	0.00551	144.11
	58	54	60	57.33	51	48	58	71	30	54	44	3	1.126	1005	0.00662	159.62
7:00	54	50	56	53.33	47	44	54	66	30	51	8	2.5	1.126	1005	0.00551	116.39
	54	50	55	53.00	47	43	53	66	30	49	8	3	1.126	1005	0.00662	126.37

Table 6.9 Thermal performance with TES 26-May-2017

Time	Plate temperature			Average Plate Temp	Glass Temperature		TES temperature		Air Temperature		Solar radiation	Air velocity	Specific Heat	Density	Mass Flow Rate	Heat gain
	(°C)			(°C)	(°C)		(°C)		(°C)		(W/m^2)	(m/s)	(J/Kg-K)	Kg/m^3	Kg/sec	Watt
	1	2	3		1	2	1	2	IN	OUT						
10:00	59	56	61	58.67	54	52	48	56	30	58	510	2.5	1006	1.113	0.00545	153.62
	58	55	60	57.67	54	51	48	56	30	56	510	3	1006	1.116	0.00656	171.64
10:45	66	62	68	65.33	63	60	54	64	32	63	613	2.5	1006	1.102	0.00540	168.40
	65	60	67	64.00	63	59	54	65	32	61	613	3	1006	1.104	0.00649	189.38
11:30	76	68	77	73.67	69	65	61	78	36	71	697	2.5	1007	1.08	0.00529	186.52
	74	67	76	72.33	68	63	61	78	36	70	697	3	1007	1.082	0.00636	217.83
12:15	84	79	86	83.00	73	69	66	86	38	77	761	2.5	1009	1.067	0.00523	205.74
	83	78	85	82.00	73	68	66	86	38	76	761	3	1009	1.069	0.00629	241.01
1:00	87	82	90	86.33	76	73	69	90	38	81	729	2.5	1009	1.061	0.00520	225.56
	86	81	89	85.33	75	71	69	91	38	79	729	3	1009	1.064	0.00626	258.82
1:45	94	88	96	92.67	79	74	73	95	40	82	670	2.5	1009	1.056	0.00517	219.28
	93	87	95	91.67	77	72	73	95	40	81	670	3	1009	1.058	0.00622	257.36
2:30	94	90	97	93.67	77	72	75	99	40	84	616	2.5	1009	1.053	0.00516	229.07
	94	89	95	92.67	76	71	75	99	40	83	616	3	1009	1.054	0.00620	268.89
3:15	90	82	94	88.67	73	68	72	97	39	81	503	2.5	1009	1.0596	0.00519	220.03
	89	82	93	88.00	73	67	72	97	39	80	503	3	1009	1.061	0.00624	258.09
4:00	85	80	87	84.00	70	66	70	95	38	77	417	2.5	1009	1.067	0.00523	205.74
	84	79	86	83.00	70	66	70	95	38	75	417	3	1008	1.07	0.00629	234.65
4:45	80	78	81	79.67	69	63	69	92	37	73	319	2.5	1008	1.075	0.00527	191.15
	78	77	79	78.00	69	63	69	92	37	72	319	3	1008	1.077	0.00633	223.42
5:30	78	72	79	76.33	65	59	65	86	33	69	201	2.5	1007	1.089	0.00534	193.44
	77	72	78	75.67	65	58	65	86	33	67	201	3	1007	1.092	0.00642	219.84
6:00	76	69	75	73.33	61	54	62	80	31	65	128	2.5	1007	1.099	0.00539	184.38
	74	67	74	71.67	61	53	62	80	31	63	128	3	1007	1.102	0.00648	208.80
6:30	69	63	71	67.67	55	50	60	76	30	62	59	2.5	1006	1.106	0.00542	174.46
	68	62	70	66.67	54	50	60	75	30	60	59	3	1006	1.109	0.00652	196.80
7:00	61	58	63	60.67	50	47	58	69	30	54	12	2.5	1005	1.12	0.00549	132.37
	61	58	63	60.67	50	47	58	69	30	51	12	3	1005	1.125	0.00662	139.61

Table 6.10 Thermal performance with TES 27-May-2017

Time	Plate temperature			Average Plate temp-	Glass Temperature		TES temperature		Air Temperature		Solar radiation	Air velocity	Specific Heat	Density	Mass Flow Rate	Heat Gain
	(°C)			°C	(°C)		(°C)		(°C)		(W/m²)	(m/s)	J/Kg-K	Kg/m³	Kg/Sec	Watt
	1	2	3	Avg	1	2	1	2	IN	OUT						
10:00	58	53	60	57.00	53	51	44	56	30	56	507	2.5	1005	1.116	0.00548	143.25
	56	52	59	55.67	53	50	45	56	30	53	507	3	1005	1.122	0.00661	152.89
10:45	64	60	67	63.67	61	58	49	63	32	62	624	2.5	1006	1.102	0.00541	163.38
	64	58	66	62.67	60	57	50	64	32	60	624	3	1006	1.106	0.00652	183.65
11:30	77	67	79	74.33	69	65	59	75	35	70	713	2.5	1007	1.084	0.00533	187.68
	74	66	77	72.33	69	63	60	76	35	69	713	3	1007	1.085	0.00640	218.99
12:15	85	79	87	83.67	74	69	65	85	38	78	784	2.5	1008	1.066	0.00524	211.14
	83	77	86	82.00	73	68	66	86	38	77	784	3	1008	1.101	0.00649	255.15
1:00	87	82	90	86.33	76	73	73	92	38	82	817	2.5	1009	1.059	0.00520	230.96
	86	81	89	85.33	75	71	73	92	38	80	817	3	1009	1.062	0.00626	265.31
1:45	96	89	97	94.00	82	75	75	95	40	84	722	2.5	1009	1.053	0.00517	229.65
	94	87	96	92.33	82	75	76	95	40	82	722	3	1009	1.056	0.00623	263.81
2:30	98	92	102	97.33	79	74	80	100	40	87	648	2.5	1010	1.048	0.00515	244.39
	96	91	100	95.67	78	73	81	100	40	85	648	3	1010	1.051	0.00620	281.59
3:15	95	86	96	92.33	75	70	77	97	39	83	542	2.5	1009	1.056	0.00519	230.31
	93	85	94	90.67	75	69	77	97	39	82	542	3	1009	1.058	0.00624	270.60
4:00	89	82	90	87.00	72	67	75	95	38	79	431	2.5	1009	1.064	0.00523	216.23
	89	81	89	86.33	72	66	75	95	38	77	431	3	1009	1.067	0.00629	247.52
4:45	84	79	86	83.00	69	63	72	93	37	75	346	2.5	1008	1.072	0.00527	201.72
	83	77	84	81.33	69	63	72	93	37	73	346	3	1008	1.075	0.00634	229.96
5:30	79	72	80	77.00	67	60	70	87	33	71	243	2.5	1007	1.085	0.00533	203.96
	78	72	79	76.33	67	58	69	86	33	69	243	3	1007	1.089	0.00642	232.73
6:00	76	69	78	74.33	64	55	67	85	31	68	159	2.5	1006	1.094	0.00537	200.04
	75	67	76	72.67	63	54	66	85	31	67	159	3	1006	1.095	0.00646	233.78
6:30	72	63	74	69.67	57	51	63	79	30	64	72	2.5	1006	1.102	0.00541	185.17
	71	62	73	68.67	56	51	63	78	30	62	72	3	1006	1.106	0.00652	209.89
7:00	64	60	66	63.33	53	49	60	74	30	58	31	2.5	1006	1.113	0.00547	154.01
	64	60	65	63.00	53	49	60	72	30	55	31	3	1006	1.118	0.00659	165.75

Table 6.11 Thermal performance with TES 30-May-2017

Time	Plate temperature			Average Plate temp	Glass Temperature		TES temperature		Air Temperature		Solar radiation	Air velocity	Specific Heat	Density	Mass Flow Rate	Heat gain
	(^oC)			(^oC)	(^oC)		(^oC)		(^oC)		(W/m^2)	(m/s)	J/Kg-K	Kg/m^3	Kg/Sec	Watt
	1	2	3		1	2	1	2	IN	OUT						
10:00	53	49	56	52.67	50	46	44	52	29	51	476	2.5	1005	1.127	0.00554	122.41
	52	49	55	52.00	50	44	44	52	29	49	476	3	1005	1.13	0.00666	133.89
10:45	59	54	62	58.33	54	50	51	61	31	59	529	2.5	1006	1.109	0.00545	153.46
	58	53	61	57.33	54	50	51	61	31	57	529	3	1006	1.113	0.00656	171.61
11:30	67	60	69	65.33	59	55	53	69	32	62	608	2.5	1006	1.102	0.00541	163.38
	66	59	67	64.00	59	54	53	69	32	60	608	3	1006	1.106	0.00652	183.65
12:15	70	63	74	69.00	64	58	56	74	34	65	703	2.5	1007	1.094	0.00537	167.77
	69	63	72	68.00	64	58	56	74	34	63	703	3	1007	1.097	0.00647	188.85
1:00	82	72	87	80.33	69	64	67	84	35	70	728	2.5	1007	1.084	0.00533	187.68
	77	71	86	78.00	69	64	67	84	35	68	728	3	1007	1.087	0.00641	212.94
1:45	92	79	92	87.67	74	69	72	90	35	75	639	2.5	1008	1.075	0.00528	212.93
	90	78	91	86.33	74	69	72	90	35	74	639	3	1008	1.077	0.00635	249.59
2:30	91	86	94	90.33	77	71	76	97	35	78	601	2.5	1008	1.07	0.00526	227.83
	90	84	90	88.00	76	70	76	97	35	76	601	3	1008	1.074	0.00633	261.66
3:15	86	80	89	85.00	72	68	72	91	35	74	518	2.5	1008	1.077	0.00529	207.99
	83	80	88	83.67	72	66	71	91	35	72	518	3	1008	1.08	0.00637	237.45
4:00	85	79	85	83.00	68	64	68	86	33	70	403	2.5	1007	1.087	0.00534	198.96
	83	78	84	81.67	68	62	68	86	33	69	403	3	1007	1.089	0.00642	232.73
4:45	76	70	78	74.67	65	62	68	84	33	67	339	2.5	1007	1.092	0.00536	183.67
	75	69	76	73.33	65	61	68	84	33	66	339	3	1007	1.094	0.00645	214.31
5:30	70	67	72	69.67	62	56	64	81	32	64	208	2.5	1007	1.099	0.00540	173.97
	68	65	71	68.00	61	55	64	81	32	63	208	3	1006	1.101	0.00649	202.41
6:00	65	63	69	65.67	60	50	61	78	30	59	131	2.5	1006	1.111	0.00546	159.23
	64	62	67	64.33	59	49	61	78	30	58	131	3	1006	1.113	0.00656	184.81
6:30	63	60	64	62.33	55	46	59	74	30	55	52	2.5	1005	1.118	0.00549	137.99
	63	59	64	62.00	55	46	59	74	30	53	52	3	1005	1.122	0.00661	152.89
7:00	58	55	60	57.67	51	42	54	69	29	52	11	2.5	1005	1.125	0.00553	127.75
	57	54	60	57.00	48	40	53	69	29	49	11	3	1005	1.13	0.00666	133.89

Table 6.12 Thermal performance with TES 02-June-2017

Time	Plate temperature			Average Plate temp	Glass Temperature		TES temperature		Air Temperature		Solar radiation	Air velocity	Specific Heat	Density	Mass Flow Rate	Heat gain
	(°C)			(°C)	(°C)		(°C)		(°C)		(W/m²)	(m/s)	J/Kg-K	Kg/m³	Kg/Sec	Watt
	1	2	3		1	2	1	2	IN	OUT						
10:00	53	48	55	52.00	54	49	41	53	29	52	499	2.5	1005	1.125	0.00553	127.75
	53	47	54	51.33	54	49	42	53	29	50	499	3	1005	1.129	0.00666	140.46
10:45	61	55	64	60.00	64	57	50	63	31	59	604	2.5	1006	1.109	0.00545	153.46
	60	54	63	59.00	64	57	50	63	31	58	604	3	1006	1.111	0.00655	177.89
11:30	72	65	74	70.33	71	62	57	73	31	67	640	2.5	1007	1.095	0.00538	195.01
	71	65	73	69.67	71	61	57	73	31	65	640	3	1007	1.099	0.00648	221.81
12:15	80	71	81	77.33	73	65	62	78	32	74	692	2.5	1007	1.082	0.00532	224.81
	79	69	80	76.00	73	64	62	78	32	73	692	3	1007	1.084	0.00639	263.83
1:00	85	75	87	82.33	76	70	69	85	33	77	657	2.5	1008	1.075	0.00528	234.22
	83	74	86	81.00	76	69	69	85	33	76	657	3	1008	1.077	0.00635	275.19
1:45	91	80	93	88.00	79	72	75	91	34	79	636	2.5	1008	1.07	0.00526	238.43
	90	78	91	86.33	78	70	75	91	34	78	636	3	1008	1.072	0.00632	280.28
2:30	94	86	96	92.00	81	74	84	98	35	83	573	2.5	1009	1.062	0.00522	252.67
	94	85	94	91.00	80	73	84	98	35	82	573	3	1009	1.064	0.00627	297.45
3:15	91	82	92	88.33	79	70	82	94	36	81	492	2.5	1009	1.064	0.00523	237.33
	90	80	90	86.67	79	70	82	94	36	80	492	3	1009	1.066	0.00628	278.99
4:00	87	80	89	85.33	78	68	78	91	36	77	411	2.5	1008	1.07	0.00526	217.24
	86	79	89	84.67	77	68	78	91	36	76	411	3	1008	1.072	0.00632	254.80
4:45	81	75	83	79.67	71	62	72	87	35	70	294	2.5	1007	1.084	0.00533	187.68
	79	73	82	78.00	71	62	72	87	35	68	294	3	1007	1.087	0.00641	212.94
5:30	74	68	76	72.67	66	60	66	82	35	64	197	2.5	1007	1.094	0.00537	156.94
	73	65	75	71.00	65	59	66	82	35	62	197	3	1007	1.097	0.00647	175.83
6:00	69	63	71	67.67	60	52	61	77	33	61	120	2.5	1006	1.102	0.00541	152.49
	68	62	70	66.67	59	51	61	77	33	60	120	3	1006	1.104	0.00651	176.77
6:30	64	58	66	62.67	55	48	58	73	32	56	62	2.5	1006	1.113	0.00547	132.01
	63	57	65	61.67	54	48	58	73	32	54	62	3	1006	1.116	0.00658	145.60
7:00	59	54	60	57.67	50	44	54	68	30	52	11	2.5	1005	1.123	0.00552	121.98
	59	52	60	57.00	49	44	54	68	30	51	11	3	1005	1.125	0.00663	139.97

Table 6.13 Thermal performance with TES 03-June-2017

Time	Plate temperature			Average Plate Temp	Glass Temperature		TES temperature		Air Temperature		Solar radiation	Air velocity	Specific Heat	Mass Flow Rate	Density	Heat gain
	(°C)			(°C)	(°C)		(°C)		(°C)		(W/m²)	(m/s)	J/Kg-K	Kg/Sec	Kg/m³	Watt
	1	2	3		1	2	1	2	IN	OUT						
10:00	54	50	57	53.67	55	50	43	54	30	53	503	2.5	1005	0.00592	1.122	136.83
	53	49	56	52.67	55	50	43	54	30	51	503	3	1005	0.00710	1.125	149.92
10:45	63	58	66	62.33	66	58	52	64	32	61	625	2.5	1006	0.00592	1.104	172.70
	62	57	65	61.33	65	57	52	64	32	60	625	3	1006	0.00710	1.106	200.09
11:30	75	67	78	73.33	72	65	58	75	32	68	653	2.5	1007	0.00592	1.092	214.60
	73	66	76	71.67	71	64	58	75	32	67	653	3	1007	0.00710	1.094	250.36
12:15	82	73	84	79.67	74	69	64	79	32	75	707	2.5	1007	0.00592	1.08	256.32
	80	72	83	78.33	73	68	65	79	32	74	707	3	1007	0.00710	1.082	300.43
1:00	86	77	88	83.67	77	71	71	87	34	78	668	2.5	1008	0.00592	1.072	262.54
	85	76	87	82.67	76	70	71	87	34	77	668	3	1008	0.00710	1.074	307.89
1:45	92	81	94	89.00	80	73	77	92	35	80	641	2.5	1008	0.00592	1.067	268.51
	91	80	92	87.67	78	71	77	92	35	79	641	3	1008	0.00710	1.069	315.05
2:30	95	87	97	93.00	82	75	86	98	36	85	591	2.5	1009	0.00592	1.058	292.67
	94	86	96	92.00	82	75	86	98	36	83	591	3	1009	0.00710	1.061	336.87
3:15	91	83	93	89.00	79	71	82	94	37	82	498	2.5	1009	0.00592	1.061	268.78
	90	80	90	86.67	79	70	82	94	37	81	498	3	1009	0.00710	1.062	315.37
4:00	88	81	90	86.33	78	68	79	91	37	78	431	2.5	1008	0.00592	1.067	244.64
	86	79	89	84.67	77	68	79	91	37	77	431	3	1008	0.00710	1.069	286.41
4:45	81	75	84	80.00	72	63	74	87	36	72	309	2.5	1008	0.00592	1.079	214.81
	80	74	84	79.33	72	63	74	87	36	69	309	3	1008	0.00710	1.084	236.29
5:30	75	69	78	74.00	66	61	68	83	36	66	213	2.5	1008	0.00592	1.075	179.01
	74	68	77	73.00	65	60	68	83	36	64	213	3	1008	0.00710	1.092	200.49
6:00	70	64	73	69.00	62	55	62	78	34	62	139	2.5	1007	0.00592	1.099	166.91
	69	63	72	68.00	60	54	62	78	34	61	139	3	1007	0.00710	1.101	193.14
6:30	65	59	68	64.00	57	50	59	75	34	58	68	2.5	1006	0.00592	1.106	142.92
	63	58	67	62.67	57	50	59	75	34	56	68	3	1006	0.00710	1.109	157.21
7:00	60	55	62	59.00	52	45	56	69	31	54	28	2.5	1005	0.00592	1.118	136.83
	59	54	60	57.67	51	44	56	69	31	53	28	3	1005	0.00710	1.12	157.06

Table 6.14 Thermal performance of SAH with TES 05-June-2017

Time	Plate temperature			Average Plate Temp	Glass Temperature		TES temperature		Air Temperature		Solar radiation	Air velocity	Specific Heat	Density	Mass Flow Rate	Heat gain
	(°C)			°C	(°C)		(°C)		(°C)		(W/m²)	(m/s)	J/Kg-K	Kg/m³	Kg/Sec	Watt
	1	2	3		1	2	1	2	IN	OUT						
10:00	60	54	62	58.67	58	51	47	58	34	59	572	2.5	1006	1.104	0.00592	148.88
	58	53	61	57.33	57	50	47	58	34	58	572	3	1006	1.106	0.00710	171.51
10:45	67	59	69	65.00	60	54	52	67	34	64	648	2.5	1007	1.095	0.00592	178.83
	65	58	68	63.67	60	54	52	67	34	63	648	3	1007	1.097	0.00710	207.44
11:30	73	65	77	71.67	70	61	59	77	34	70	701	2.5	1007	1.085	0.00592	214.60
	72	64	76	70.67	70	60	59	77	34	69	701	3	1007	1.087	0.00710	250.36
12:15	81	72	85	79.33	73	65	65	84	36	75	733	2.5	1008	1.074	0.00592	232.71
	80	71	84	78.33	73	64	65	84	36	74	733	3	1008	1.075	0.00710	272.09
1:00	88	77	91	85.33	79	70	74	91	37	79	720	2.5	1009	1.066	0.00592	250.86
	86	76	89	83.67	77	70	74	91	37	78	720	3	1009	1.067	0.00710	293.86
1:45	91	80	94	88.33	79	73	75	96	37	81	707	2.5	1009	1.062	0.00592	262.80
	90	79	92	87.00	77	71	75	96	37	80	707	3	1009	1.064	0.00710	308.20
2:30	93	83	96	90.67	80	70	84	99	39	83	658	2.5	1009	1.056	0.00592	262.80
	93	81	94	89.33	79	70	85	100	39	81	658	3	1009	1.059	0.00710	301.03
3:15	91	79	93	87.67	76	67	81	95	39	81	511	2.5	1009	1.059	0.00592	250.86
	90	79	92	87.00	75	67	81	95	39	80	511	3	1009	1.061	0.00710	293.86
4:00	86	76	88	83.33	73	64	79	91	37	78	468	2.5	1009	1.067	0.00592	244.89
	85	75	88	82.67	72	64	79	91	37	78	468	3	1009	1.067	0.00710	293.86
4:45	82	75	84	80.33	70	62	73	87	36	72	327	2.5	1008	1.079	0.00592	214.81
	80	73	83	78.67	70	62	72	87	36	70	327	3	1008	1.082	0.00710	243.45
5:30	78	70	79	75.67	66	63	68	83	36	66	231	2.5	1007	1.089	0.00592	178.83
	77	79	77	77.67	65	61	68	83	36	65	231	3	1007	1.09	0.00710	207.44
6:00	69	64	72	68.33	61	54	63	78	34	62	146	2.5	1007	1.099	0.00592	166.91
	69	63	71	67.67	60	53	63	78	34	61	146	3	1007	1.101	0.00710	193.14
6:30	65	59	68	64.00	55	49	59	72	33	57	82	2.5	1006	1.109	0.00592	142.92
	65	58	68	63.67	54	49	59	72	33	56	82	3	1006	1.111	0.00710	164.36
7:00	60	55	63	59.33	50	44	54	68	32	54	38	2.5	1006	1.116	0.00592	131.01
	60	53	61	58.00	49	44	54	68	32	52	38	3	1006	1.12	0.00710	142.92

CHAPTER 7

RESULTS AND DISCUSSION

In the previous chapter experimental observations were added in a tabular format. In this chapter calculations of observations has been summarize. To obtain the results from the observations basic thermal relation were used. Effect of temperature on specific heat and density of air has been taken into consideration. With the increases in temperature of air specific heat increases and density decreases. Value of specific heat and density were taken at average temperature of inlet and outlet of air.

7.1 Performance analysis of SAH:

Constants for calculation are:

Velocity of air coming out from the blower = 2.5 m/sec and 3 m/sec

Inlet and outlet diameter of the pipe = 5 cm

Cross-section Area of the pipe $= \frac{\pi}{4} D^2$

$= \frac{\pi}{4} (5)^2 \ cm^2$

$= 0.001965 \ m^2$

Observations were taken at 1:00 P.M. on 11 May 2017 for sample calculation.

Air inlet temperature = 33 ^oC

Air outlet temperature = 85 ^oC

Average temperature = 59 ^oC

Properties of air at average temperature are (Appendix-B):

Atmospheric pressure 1 Bar

Density of air = 1.049 Kg/m^3

Specific heat = 1009 J/Kg-K

Mass flow rate of air = ρ*A*V

= 1.049*2.5*0.001965 = 0.00515 Kg/sec

Heat gain by the air = $\dot{m}*C_p\,(T_{out} - T_{in})$

= 0.00515*1009*52 = 270.08 W

Solar input = I*A

= 837* (1.25*0.8) = 837 W

Efficiency of Solar air heater = heat utilized / Solar input

= $\dot{m}*C_p\,(T_{out} - T_{in}) / I*A$

= 270.08/837 = 0.32267 = 32.27 %

All the set of observation were calculated as shown in the above section 7.1 Performance analysis of SAH. All the results are plotted on the graphs. Graphs are plotted for solar intensity, average absorber plate temperature, air outlet temperature, heat gain by the flowing air, total heat gain with respect to time for two different air velocity.

SAH with TES was compared with SAH without TES; therefore a graph was plotted between average total heat gain of all the days. Graphs from 7.1 to 7.5 represent the performance of solar air heater without TES and graphs from 7.6 to 7.10 represent the performance of solar air heater with TES.

To compare both the segment of solar air heater with and without TES graph 7.11 and 7.12 were plotted between time and the average total heat gain.

7.2 Effect of using Thermal energy storage:

When air flow velocity was 2.5 m/s

Total average heat gain without TES = 2342.33 Watt

Total average heat gain with TES = 2672.30 Watt

Performance improved by = 329.97 Watt

Percentage improvement in performance = 14.08 %

When air flow velocity was 3 m/sec

Total average heat gain without TES = 2617.04 Watt

Total average heat gain with TES = 3059.14 Watt

Performance improved by = 442.10 Watt

Percentage improvement in performance = 16.89

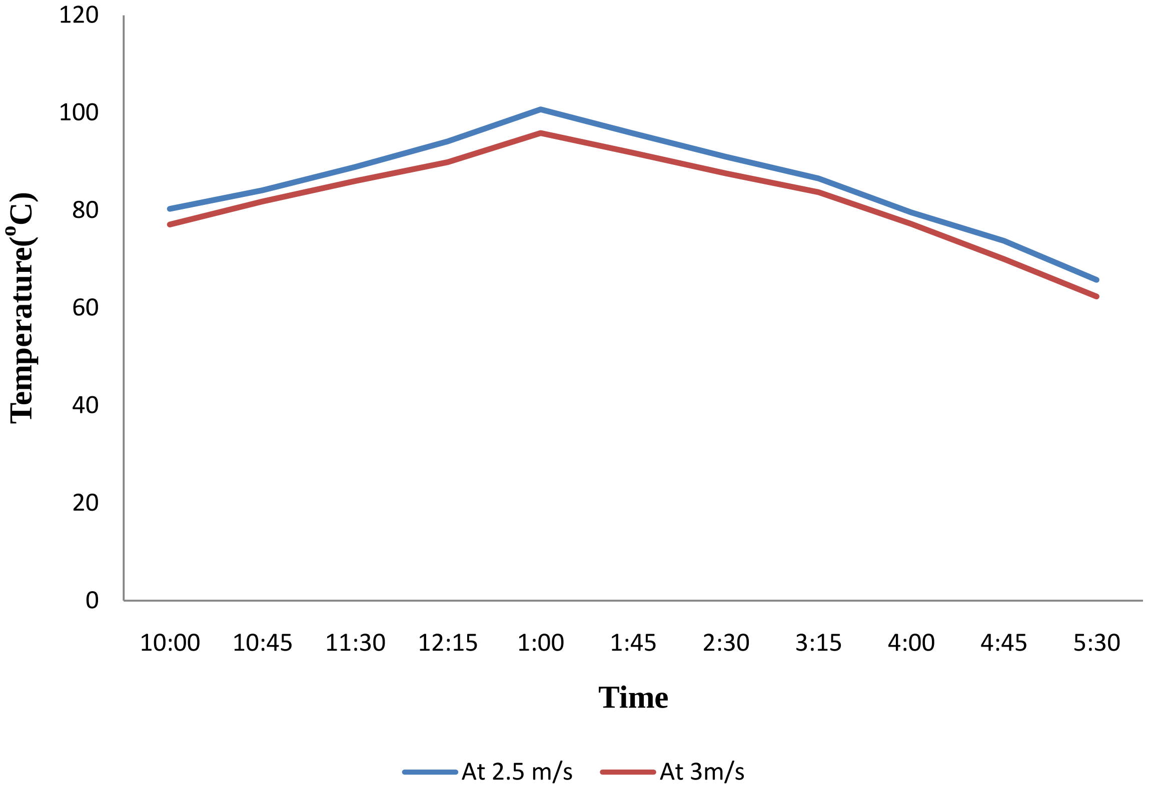

Fig 7.1 Time VS Absorber Plate Temperature

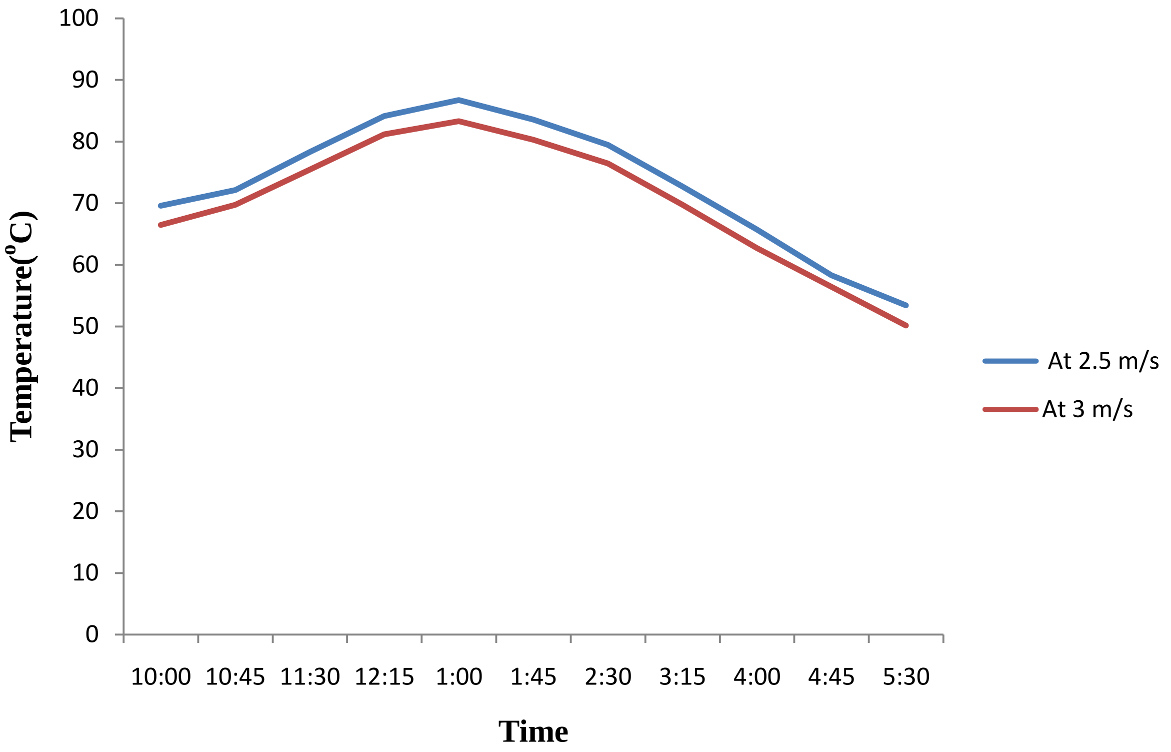

Fig 7.2 Time VS Air Outlet Temperature

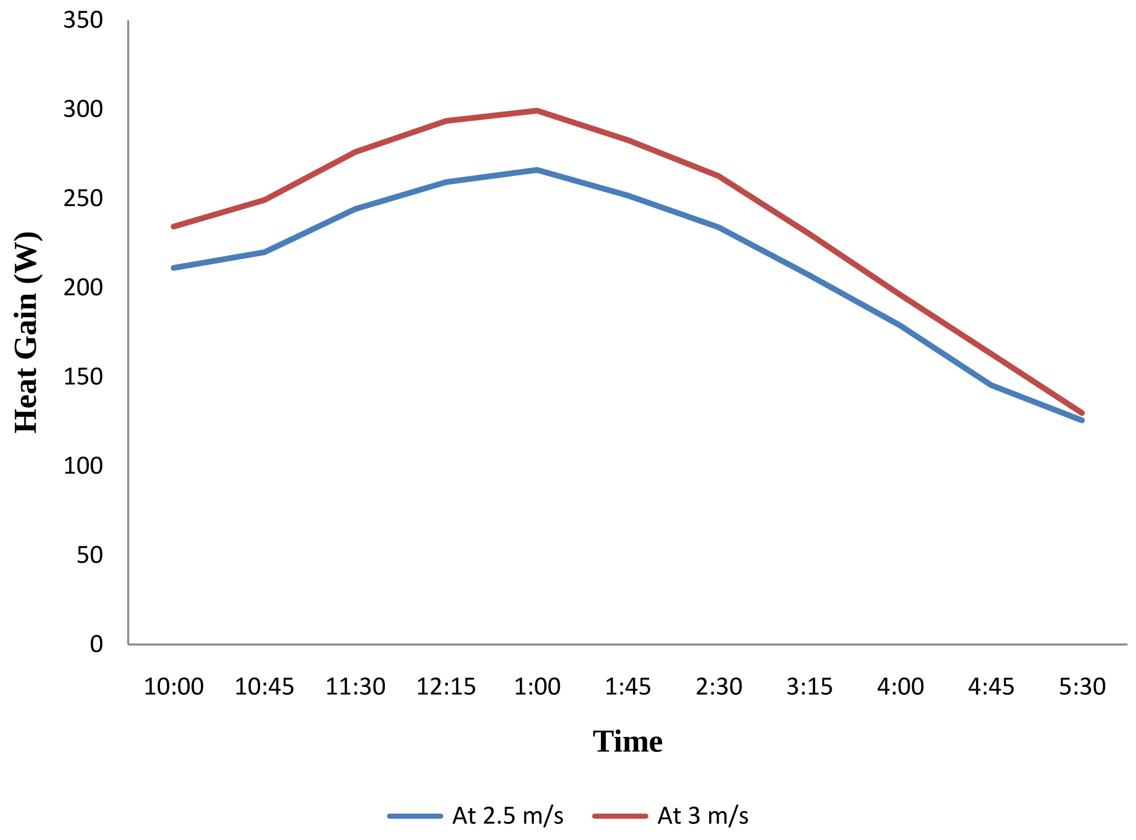

Fig 7.3 Time VS Heat gain

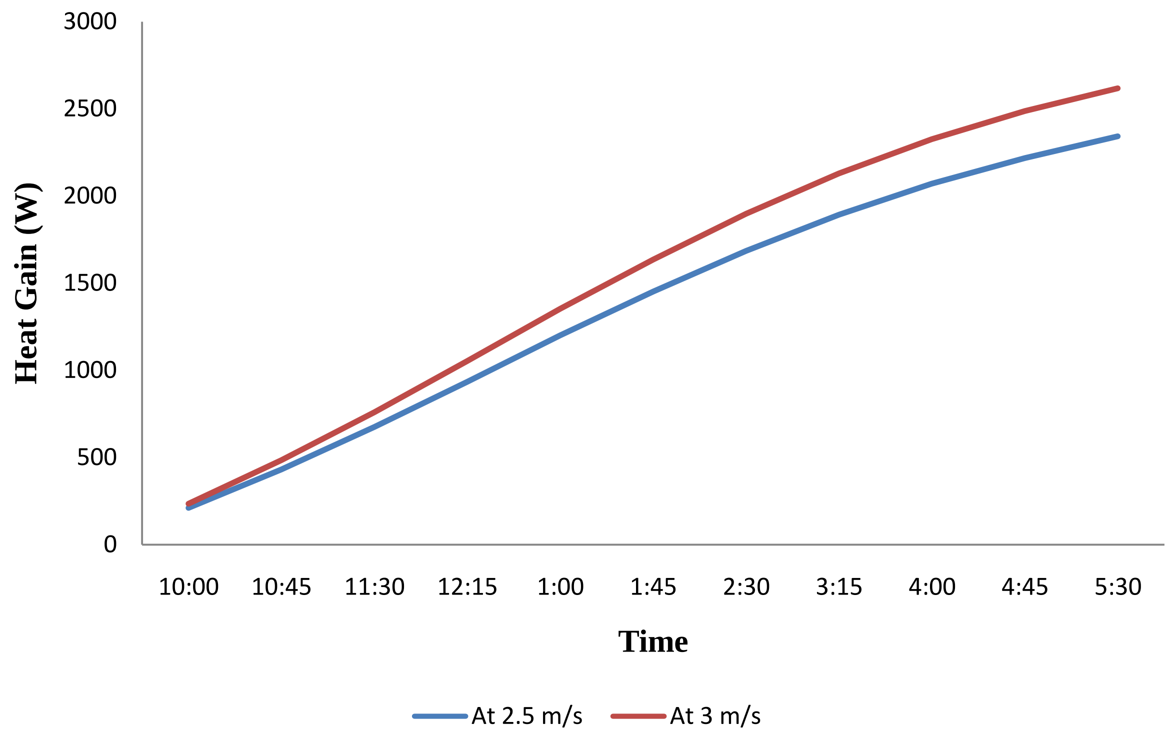

Fig 7.4 Time VS Collective Heat Gain

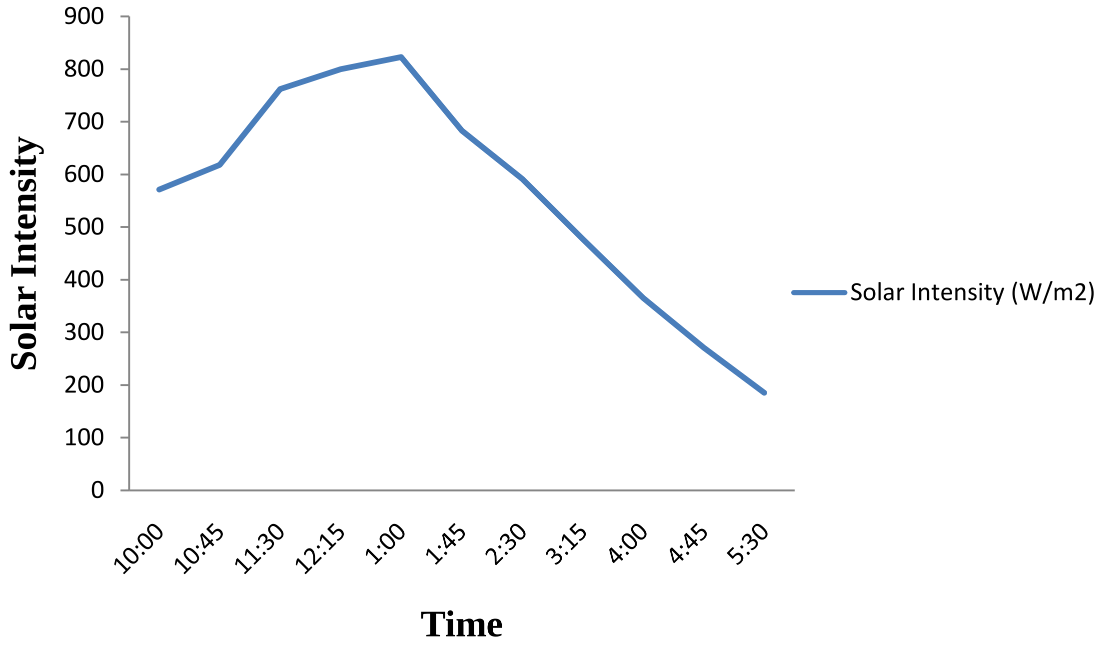

Fig 7.5 Time VS Solar Intensity

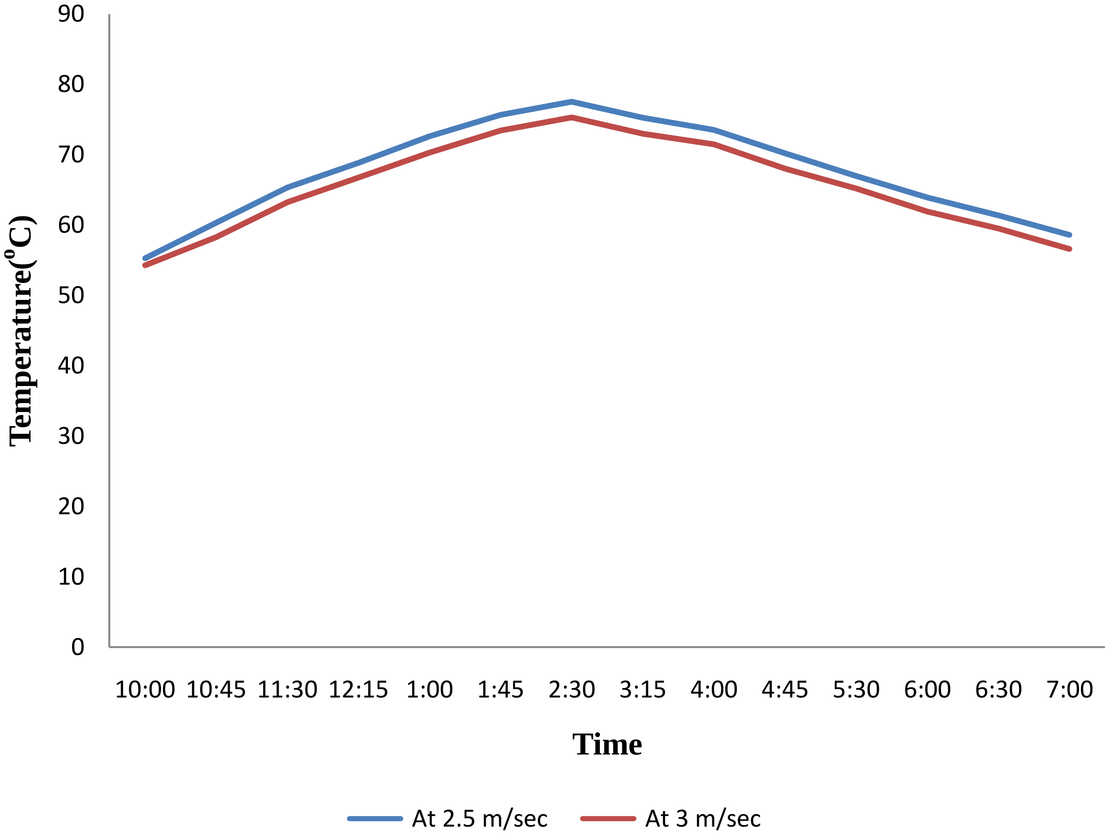

Fig 7.6 Time VS Absorber Plate Temperature

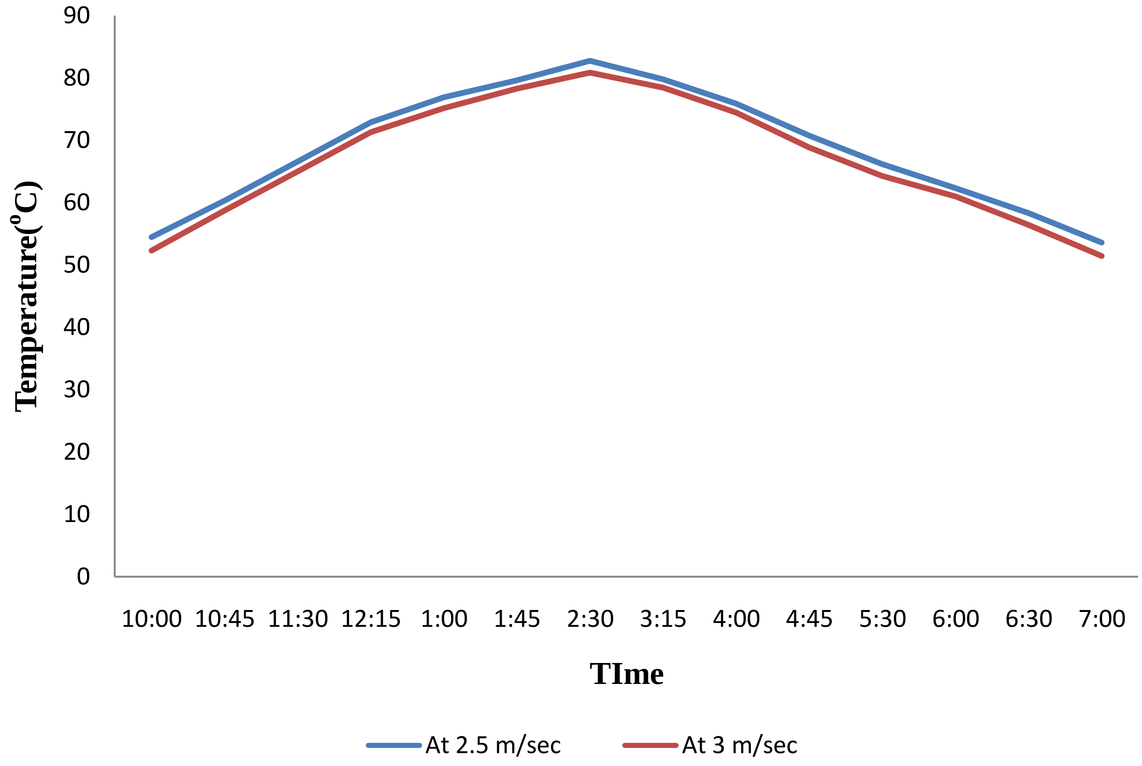

Fig 7.7 Time VS Air Outlet Temperature

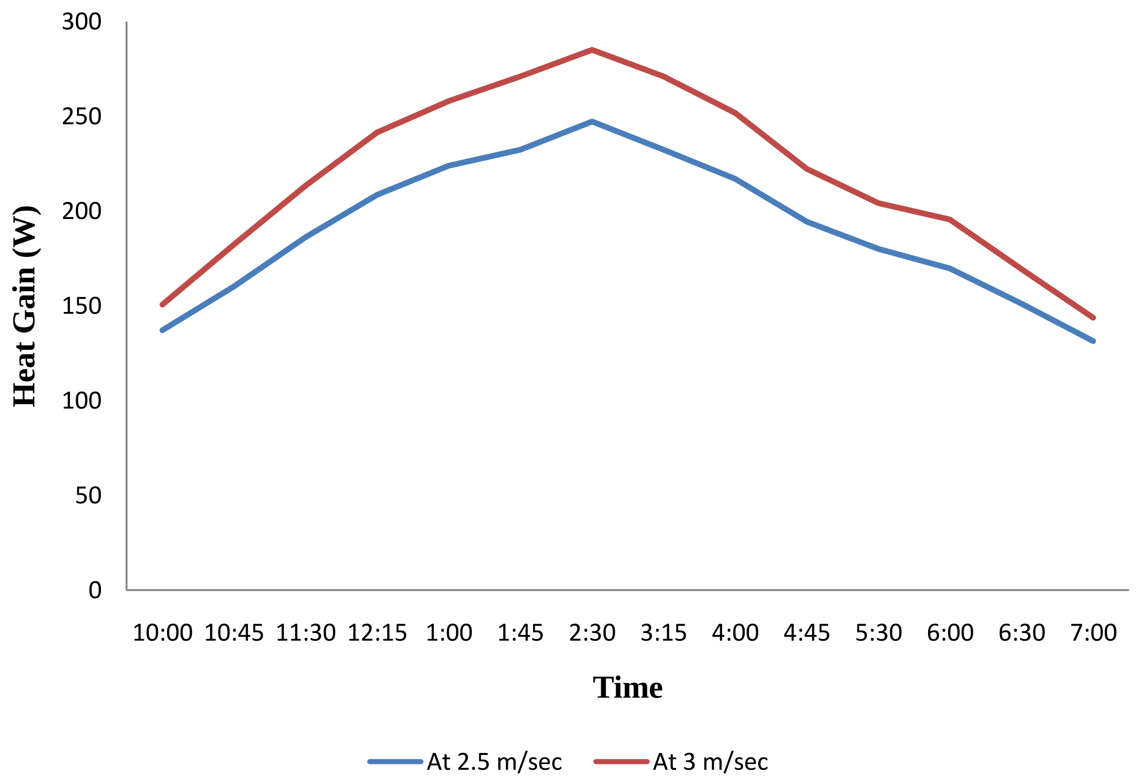

Fig 7.8 Time VS Heat Gain

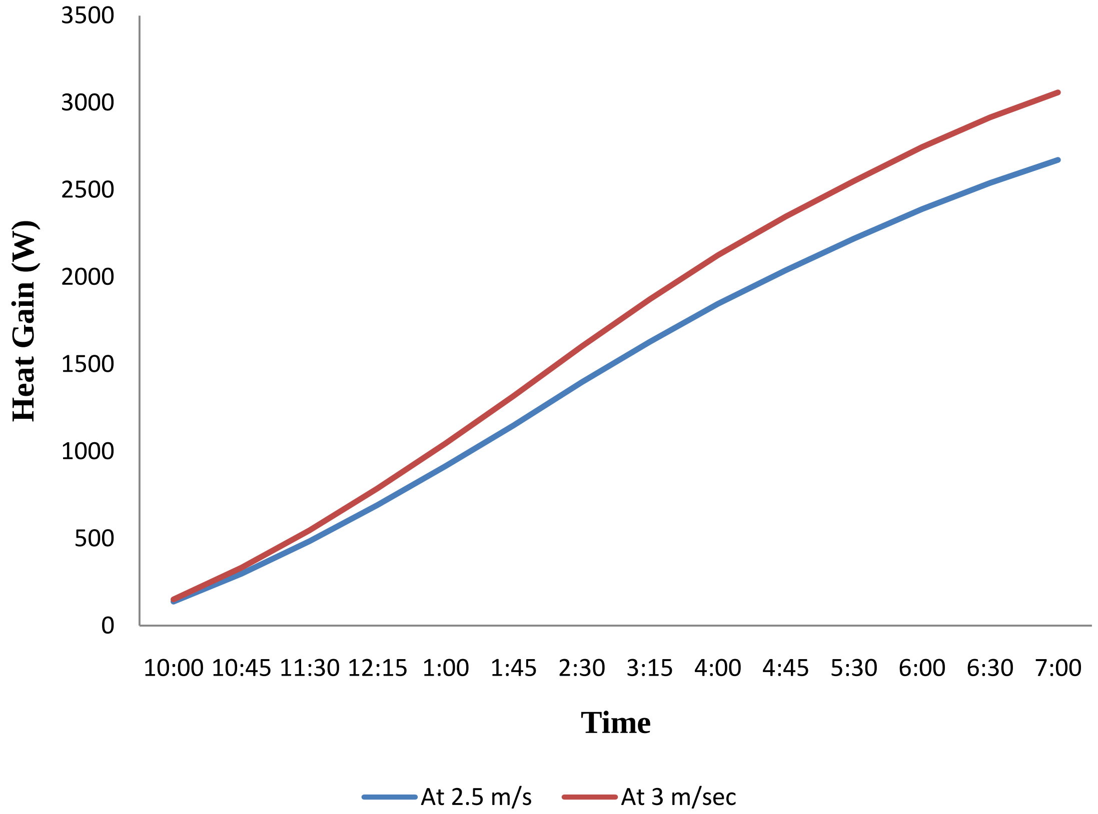

Fig 7.9 Time VS Collective Heat Gain

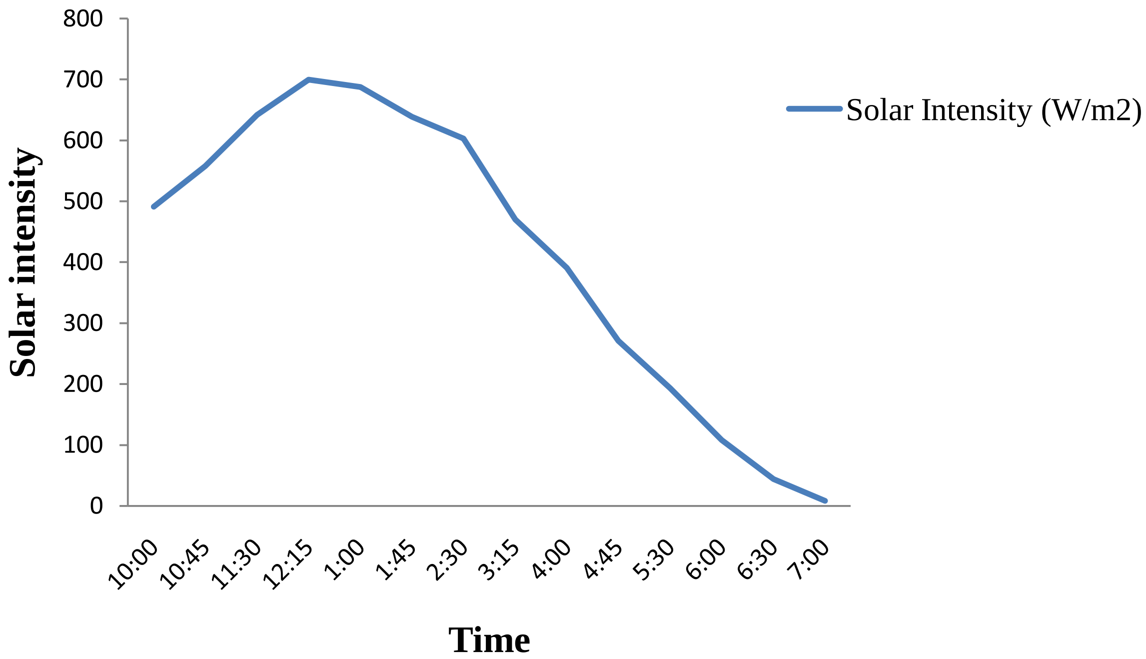

Fig 7.10 Time VS Solar Intensity

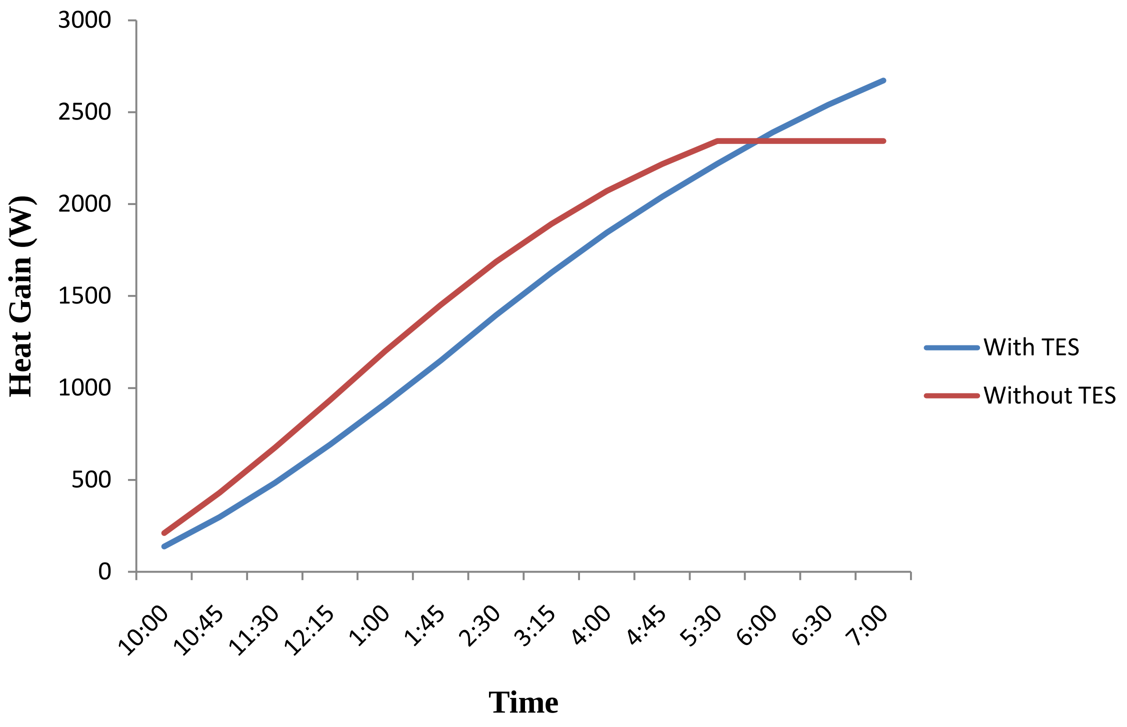

Fig 7.11 Time VS Collective Heat Gain at 2.5 m/s

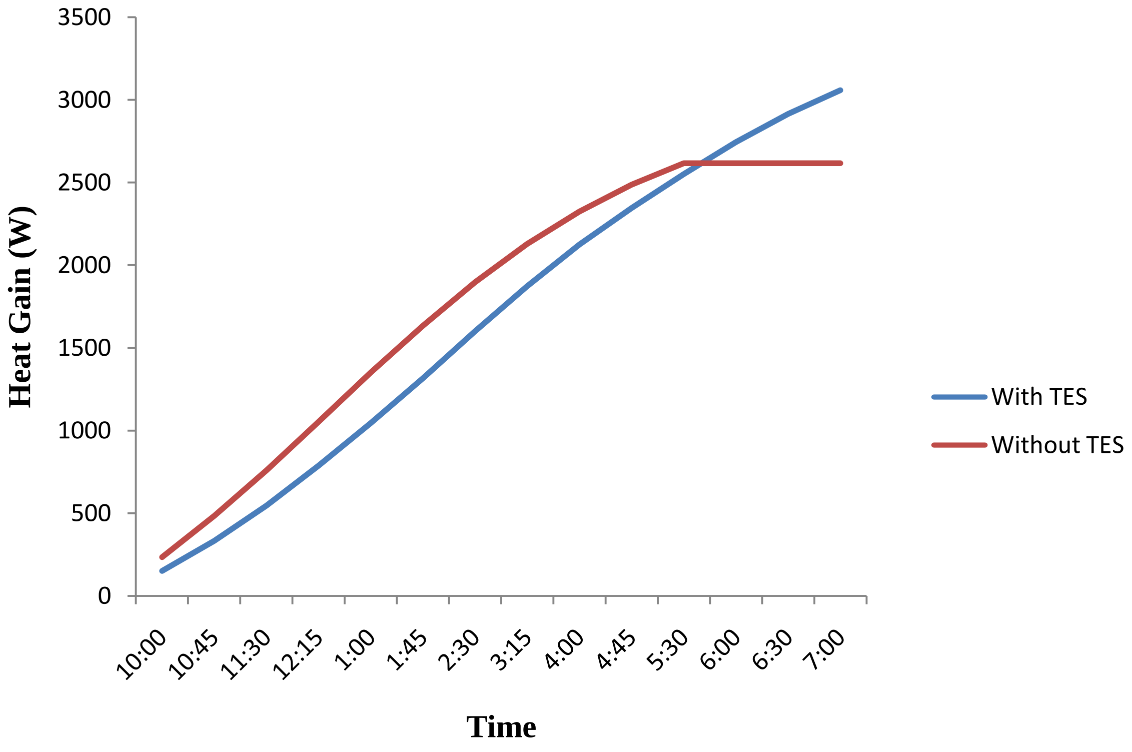

Fig 7.12 Time VS Collective Heat Gain at 3 m/s

CHAPTER 8

CONCLUSIONS

A detailed study was carried out for the design of fin type solar air heater integrated with thermal energy storage. Experiment was performed on newly design SAH. Performance of solar air heater was analyzed and comparison was done for collective heat gain by the solar air heater for both the condition. It SAHs have various applications like space heating, drying agriculture crops, seeds, dry fruits, etc. Solar air heater can be used to reduce load of space heating during winter.

Experimentation has been carried out for performance analysis of fin type solar air heater with and without TES. Total 14 set of reading were observed from 11 May to 5 June 2017.Conclusions are based on the result obtain from the observation.

1. It was observed that average absorber plate temperature of *solar air heater without thermal energy storage* was more compared to *solar air heater with thermal energy storage* as some part of the energy absorbed by the absorber plate transferred to the heat storage fluid.
2. Temperature gain in air (with different air velocity) was found more in*solar sir heater without thermal energy storage* since temperature of absorber plate was more.
3. Heat gain by the air at a particular time for both the conditions for solar air heater was found more at higher velocity of air.
4. Heat gain by the air at a particular time of time was found more in solar air heater without thermal energy storage since temperature in air was more.
5. Total heat gain by the air for a complete day was found more with *solar air heater with thermal energy storage*. Use of thermal energy storage fluid allow to store heat in day time and deliver that stored heat when require.

Table 8.1 Collective heat gain for a day

Air flow velocity	SAH with TES	SAH without TES
2.5 m/s	2672.30 Watt	2342.33 Watt
3 m/s	3059.14 Watt	2617.04 Watt

6. Improvement in performance was found if thermal energy storage medium used in the solar air heater.

Table 8.2 Performance Improvement Data

Air flow velocity	Percentage improvement
2.5 m/sec	14.08
3 m/sec	16.89

8.1 Future Scope:

Design, development and performance analysis of solar air heater with and without thermal energy storage gives the following recommendation for future scope of the work

Experiment may be performed on various air flow velocity to understand the effect of air flow velocity on the performance of solar air heater.

Use of selective coating on absorber plate such as Nickel based coating, chromium based coating, etc. which improve the absorptivity of absorber plate.

Use glass cover of better transmissivity which allow transmission of more amount of solar radiation.

System simulation on TRNSYS may be carried out to optimize the present system so that it can be used in much effective manner.

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