Modelling, Simulation and Fabrication of a Hybrid Solar Dryer for the Drying of Medicinal and Aromatic Plants (MAPs)-Case Study Khyber Pakhtunkhwa (KPK), Pakistan.

By

Mariam Mahmood
NUST201260740MCES64112F

Supervised by

Dr. Parvez Akhtar

Center for Energy Systems (CES)
National University of Sciences and Technology (NUST)
H-12, Islamabad 44000, Pakistan

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Certificate

This is to certify that work in this thesis has been carried out by Ms. Mariam Mahmood and completed under my supervision in solar thermal laboratory, Centre for Energy Systems, National University of Sciences and Technology, H-12, Islamabad, Pakistan.

Supervisor: _______________

Dr. Parvez Akhtar
Centre for Energy Systems
NUST, Islamabad

GEC member # 1: _______________

A/Prof. Ahmad Sohail
College of EME
NUST, Rawalpindi.

GEC member # 2: _______________

Dr. Adeel Waqas
Centre for Energy Systems
NUST, Islamabad

GEC member # 3: _______________

Dr. Yousuf Jamal
Institute of Environmental Sciences and Engineering (IESE)
NUST, Islamabad

HoD-CES _________________

Dr. Zuhair S Khan
Centre for Energy Systems
NUST, Islamabad.

Principal/ Dean _______________

Dr. M. Bilal Khan
Centre for Energy Systems

NUST,Islamabad.

DEDICATION

I dedicate this work to my beloved parents, respected teachers and friends without whom I would not have been able to achieve success in life

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First and above all, I praise **The Allah Almighty,** the almighty for providing me this opportunity and granting me the capability to proceed successfully. This thesis appears in its current form due to the assistance and cooperation of several people. I would therefore like to offer my sincere gratitude to all of them.

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ABSTRACT

Due to escalating prices of fossil fuels and their dwindling supply worldwide, solar energy is the best alternative to conventional fuels. Pakistan, being located in the sunny belt, has enormous potential for solar PV and thermal applications.

Solar thermal energy can find potential applications in drying of agricultural products and medicinal and aromatic plants (MAPs) by using solar dryers. This study develops an indirect-mode forced convection hybrid solar dryer model at commercial scale and a lab scale prototype as well. Commercial scale model has been proposed after careful assessment of Maps' drying load, equilibrium moisture content and metrological data of target areas in KPK-Pakistan, through extensive literature review and field visits.

Lab scale prototype of solar dryer consists of a flat plate solar collector, drying chamber, biomass burner, heat exchanger, temperature sensors and two DC fans. Biomass burner serves as the supplement heat source in case of rainy or cloudy weather. And fans force the hot air from solar collector or biomass burner to the drying chamber, at required flow rate. Hot air moves through perforated trays inside the drying chamber from bottom inlets, and absorbs moisture from the products. Then moist air exits through the top vent.

In order to predict the thermal performance of solar collector under varying ambient conditions and flow rate, a simulation algorithm has been developed. This algorithm involves matrix inversion technique in MATLAB. Modeling and simulation of dryer chamber has been done using FLUENT. Simulation results indicate the temperature distribution and velocity gradient within chamber, under testing conditions. Based on modeling and simulation results, lab scale prototype of solar dryer has been fabricated at Manufacturing Resource Center (MRC)-NUST. For experimental verification of dryer performance several drying tests were conducted for different types of MAPs, under ambient conditions. The comparison between computed and experimental results for thermal performance of solar collector and drying chamber indicated a satisfactory convergence.

Key words: thermal efficiency, heat exchanger, equilibrium moisture content, mathematical modeling, optimum temperature.

LIST OF FIGURES

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LIST OF JOURNALS/CONFERENCE PAPERS

1. ‘Thermal Performance of Flat Plate Solar Air Collectors: Mathematical Model and Simulation’. Journal: Environmental Progress and Sustainable Energy.
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*Attached in Annexure-I

**Attached in Annexure-I I

LIST OF ABBREVIATIONS

PMD	Pakistan Meteorological Department
AEDB	Alternative Energy Development Board
PCRET	Pakistan Council of Renewable Energy Technologies.
GI	Galvanized iron
A	Flow cross sectional area (m^2) [width of collector* air gap between absorber and
Cp	Air specific heat (1009 J/kg-K)
Dh	Hydraulic diameter (m)
$h_{1,2}$	Forced convection heat transfer coefficients (W/m^2-K)
H	Natural convection heat transfer coefficients (W/m^2-K)
h_{rs}	Radiation heat transfer coefficient from top cover to the sky. (W/m^2-K)
h_{r21}	Radiation heat transfer between cover and absorber. (W/m^2-K)
Hw	Wind convection heat transfer coefficient (W/m^2-K).
H	Incident global radiation (W/m^2)
K	Thermal Conductivity of air (W/m-k)
k_{bi}	Thermal conductivity of bottom insulation (W/m-k)
L	Collector length (m)
$\dot{m}$	Air mass flow rate (kg/s)
$S_{1,2}$	Solar radiation absorbed by cover and absorber (W/m^2)
$T_{1,2}$	Temperature of cover and absorber (K)
T_s	Sky temperature (k)
T_{fo}	Mean air temperature at the collector outlet (k)
T_{fo}	Mean air temperature at the collector outlet (k)
U_b	Bottom heat loss coefficient (W/m^2-K)

U_t	Top heat loss coefficient (W/m^2-K)
V	Wind speed (m/s)
W	Width of collector (m)
x_{bi}	Bottom insulation thickness (m)

Greek Symbols

$\alpha_{1,2}$	Absorptivity of top glass cover and absorber
$\epsilon_{1,2}$	Emissivity of top glass surface and absorber,
μ	viscosity of air (kg/m-s)
T	Transmissivity of the top glass,
σ	Stefan Boltzmann constant ($5.67*10^{-8}$ W m^{-2} K^{-4})

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CHAPTER 1

INTRODUCTION

1.1 Medicinal and Aromatics Plants (MAPs)

In medical terminology, medicinal plants are defined as the species that possess definite pharmacological attributes and thus cure various ailments in human body. This medication activity of medicinal plants is due to the presence of active chemical constituents in different parts like roots, stems, fruits or leaves. These chemicals react simultaneously to attain equilibrium in the body as they do in the plant, and so induce moderate, tender healing within body tissues [1].

The term ‘aromatic’ has been used in a broader sense: this characterizes the plants having an aroma or fragrance, while the word aroma also implies the taste of material. These aromatic plants are extensively used in food processing industry for spicing, seasoning, flavoring and coloring.

Biologically active ingredients in medicinal and aromatic plants can be classified as Alkaloids, Glycosides and essential oils and some secondary metabolites which are the end products of metabolic processes within plant body. Physical environmental conditions like light, temperature, rain fall and soil characteristics are the determining factors for growth and development of MAPs and their metabolites.

Thus these medicinal and aromatic plants and their extracts became the main source of medicines worldwide, and have always found potential applications in perfumery markets, cosmetics, medicines and cooking. And according to old traditions and myths, these plants have “magical” curing powers against numerous diseases..

Use of medicinal plants and herbs to cure diseases and heal physical sufferings dates back to earliest centuries, in fact history of medicinal plants is associated with human civilization. India, Middle East, Egypt, Greece and Rome civilizations are considered as birth place of MAPs [3].

Knowledge of herbs and traditional medicines was based on myths and speculations. For centuries, these plants have been the main source of primary health care worldwide. However, in 20^{th} century, trend of medicinal plants and traditional herbs faced a rapid decline because of growing research interests in synthetic drugs for curing ailments.

But now due to awareness about adverse side effects of artificial chemicals, medicinal plants are gaining their momentum again. Traditional medicines contain natural ingredients, so are chemically balanced, more effective and have no side effects as compared to their synthetic counterparts. Thus herbal medicine is again securing a strong position worldwide, along with Traditional Chinese Medicine, Osteopathy, and Homeopathy [4].

According to literature review about 20,000 medicinal plant species are being used worldwide. Conferring to W.H.O report (2002), 70 % of world population still uses traditional herbs to cure diseases. In sub-continent, herbal medicines have been used extensively for centuries. According to W.H.O survey, traditional physicians treat 65% patients in Srilanka, 60% in Indonesia, 75% in Nepal, 85% in Mayanmar, 80% in India and 90% in Bangladesh. In Pakistan, 60% of the rural population still relies on herbs as primary medical treatment [1].

This global renaissance of medicinal plants usage presents potential economic opportunities for the developing nations particularly. But on the other hand, unsustainable collection and over exploitation to gain short term monetary benefits, has become a threat for the existence of these high economic value plants and unique flora. And this is becoming a grave concern in many parts of the world except India and China, where MAPs utilization and processing chain is more developed.

The lack of awareness on the part of collectors, unsustainable harvesting, dearth of modern post-harvest operations like drying, extraction, purification, packaging and restricted market access are some of the tailbacks for the emergence of herbal industry in developing countries. All these factors also critically damage the quality and quantity of drugs. Consequently final products are far below the standards of pharmaceutical industry. There is dire need to harness these resources on sustainable basis to uplift the socio-economic conditions of developing countries.

1.2 Maps Potential In Pakistan

Pakistan is blessed with diverse and unique flora, comprising around 6000 plant species. Due to lack of modern health facilities, 80% of the population still relies on traditional herbs to complement allopathic medicines [5]. According to MEDA report (2010), around 700 plant species are used for medicinal and aromatic purposes in the Himalayan region. An estimated 1.2 to 1.5 million people, mostly women, are involved in collection of medicinal plants in KPK province. So this is a great source of income for many households especially in the mid and upper highlands.

The northern areas of Pakistan have rich resources of high economic value medicinal plants. The Himalayas, Kara Korums and Hindu-Kush mountain ranges offer vast habitats of unique flora. Ethno-botanical study conducted in Dir Kohistan Valleys revealed that local community uses 65 medicinal species belonging to 50 families to cure various ailments. But over exploitation of valuable plants, lack of awareness about conservation among locals and negligence of forest officials are potential threats for this unique biodiversity [6].

The temperate forests of Neelum valley in Azad Jammu and Kashmir support great ecosystem diversity, wide vegetation zones. This area is also blessed with enormous variety of high quality herbs. For decades, local community has been dependent on traditional medicines as the only available medication and also a source of income. Study reveals that about 60% of the population is involved in collection of medicinal plants, so this has become their potential source of income. Total of 67 medicinal species have been identified that are being used for curative purpose against 32 diseases.

Swat valley in Hindu-Kush mountains of Pakistan, is called Switzerland of the sub-continent. Along with many scenic places, this valley is also rich in medicinal flora and high value herbs. According to an ethno-botanical study conducted there, about 49 medicinal plants of 32 families are collected and dealt in herbal market of Swat. These are also exported to other parts of the country. The assessment of conservation status reveals 49% of these high economic value plants are threatened due to un-sustainable harvesting by locals [1].

Thus upper highlands of Pakistan are blessed with herb or medicinal species and thus huge growth potential exists there. There is dire need to harness these resources on sustainable basis to conserve this valuable resource and to the uplift the socio-economic conditions of the area.

1.3 Solar Energy Potential In Pakistan

Pakistan, being located in the sunny belt, has immense potential of solar energy. And this source is abundantly available all across the country. The country receives average global irradiation of 200-250 Watt/m^2-day, with about 1500-3000 sunshine hours per annum. Particularly the south western part of Balochistan and north eastern part of Sindh are blessed with huge solar potential, where they have global insulation of 19-20 MJ/m^2-day (1.93–2.03 MWh/m^2) and 8-8.5 sunshine hours daily.

Thus Pakistan has enormous solar potential for solar PV and thermal applications. Despite of these ideal conditions, we are unable to exploit solar energy at its full, thus use of solar energy for power generation or heating is still in infancy.

Solar thermal energy can find potential applications in drying of agricultural products and medicinal plants by using solar dryers. Due to escalating prices of fossil fuels and their dwindling supply, solar drying is the best alternative to conventional fuel drying. But due to lack of awareness among locals and absence of basic infrastructure, tons of fruits like apricots and high economic value plants are being wasted every year in northern areas of Pakistan [7].

However, due to joint efforts of AEDB and PCRET in last decade, solar dryers, solar water heaters and solar cookers have been provided in some rural areas of KPK and Sindh. But this is limited to very small scale. And total installed thermal units are even less than 10,000 all across the country [8].

1.4 MAPs Drying

Moisture content is the most critical factor in determining the physical and chemical properties of MAPs and for their long term preservation. Thus drying is the first and most essential step in post-harvest processing of medicinal plants. Drying is defined as: ‘the process of reducing the plants natural moisture content up to stable or equilibrium moisture content to prevent the enzymatic and microbial activity'.

Consequently it increases the shelf life of plants for the long term preservation. Drying also assists in transport and storage of plants due to reduction in volume and weight. Consequently it contributes to supply chain and marketing of medicinal plants [9].Drying process of MAPs must fulfil the following requirements in order to preserve the quality of dried products:

1. Moisture content must be reduced up to an equilibrium level defined by storage standards for certain temperature and air humidity.
2. Colors, flavors, aroma and active ingredients need to be preserved with no or minimum deterioration.
3. Microbial count must be below the standard limits, and without applying any chemical additives.

Medicinal plants are mostly dried by traditional methods such as open sun drying or drying in the shade, without using supplementary energy source. These methods have many draw backs like:

1. Direct exposure to intensive solar radiations has adverse effects on quality of MAPs, thus causing loss of active ingredients and essential oils.
2. Ambient conditions such as high temperature and air humidity promotes mold development and microbial activity which hinders the long term preservation of herbs.
3. Traditional drying methods cannot handle large capacity.
4. Dried products are far below the international quality standards.

Thus to achieve final dried products of international pharmaceutical standards, modern technical drying systems such as solar dryers are indispensable [10].

To preserve the active ingredients and essential oils within medicinal plants, low drying temperature (around 50-60^{o}C) is recommended, thus it prolongs the drying duration. Drying process incurs 30-50% of the total processing cost of medicinal plants. Thus it is critical to identify the factors responsible for high cost.

One of the substantial factors is energy demand of drying process, which has tremendously increased due to high prices of conventional fuels. High energy demand of

MAPs drying is due to high moisture content of flowers, leaves or fruits to be dried. Thus heat requirement is two folds as compared to that required for grain drying, with equal quantity to be dried. That is why energy requirement of drying consumes major expenses in drying MAPs drying.

Moreover drying parameters like dryer design, optimum drying temperature and humidity, operational method and supplement energy source are very critical and influential in terms of quality of herbs. Thus these require extensive research and crucial monitoring to get the dried herbs of international pharmaceutical standards [11].

1.5 Research Objectives

Overall the broad objective of the research is to develop and study the forced convection hybrid solar dryer for MAPs drying.

Specifically the research will focus on:

i. Study the parameters and factors that govern the performance of a solar dryer through the literature review, including dryer designs, types and optimum drying conditions

ii. Simulation of thermal performance of the flat plate glazed solar collector using MATLAB software.

iii. Modeling and simulation of dryer chamber using FLUENT software, to analyze the temperature distribution within chamber.

iv. Designing and the fabrication of the hybrid solar dryer based on the modeling results.

v. Experimental verification of dryer performance under ambient conditions.

1.6 Thesis Organization

Chapter one presents the background and objectives of this research work. A short review of the MAPs potential in Pakistan, and importance of MAPs drying is also included. And this chapter also emphasizes on the solar dryer as an alternative technology for MAPs drying.

Chapter two is the comprehensive literature review of experimental and theoretical work done on solar dryer technology. This chapter covers the key aspects of the research activity like dryer designs, optimum drying conditions, design and thermal performance of flat plate solar collectors.

Chapter three deals with methodology and approach towards research work. It describes the mathematical modelling, simulation and fabrication of lab scale prototype of solar dryer.

Chapter four presents the experimental work conducted in this study. It also describes the experimental procedures in detail.

Chapter five designates the analysis, discussion of experimental results obtained and comparison between experimental and simulated results. It also includes the commercial scale model of solar dryer.

Chapter six draws important conclusions from the research conducted and also discuss the potential for future work.

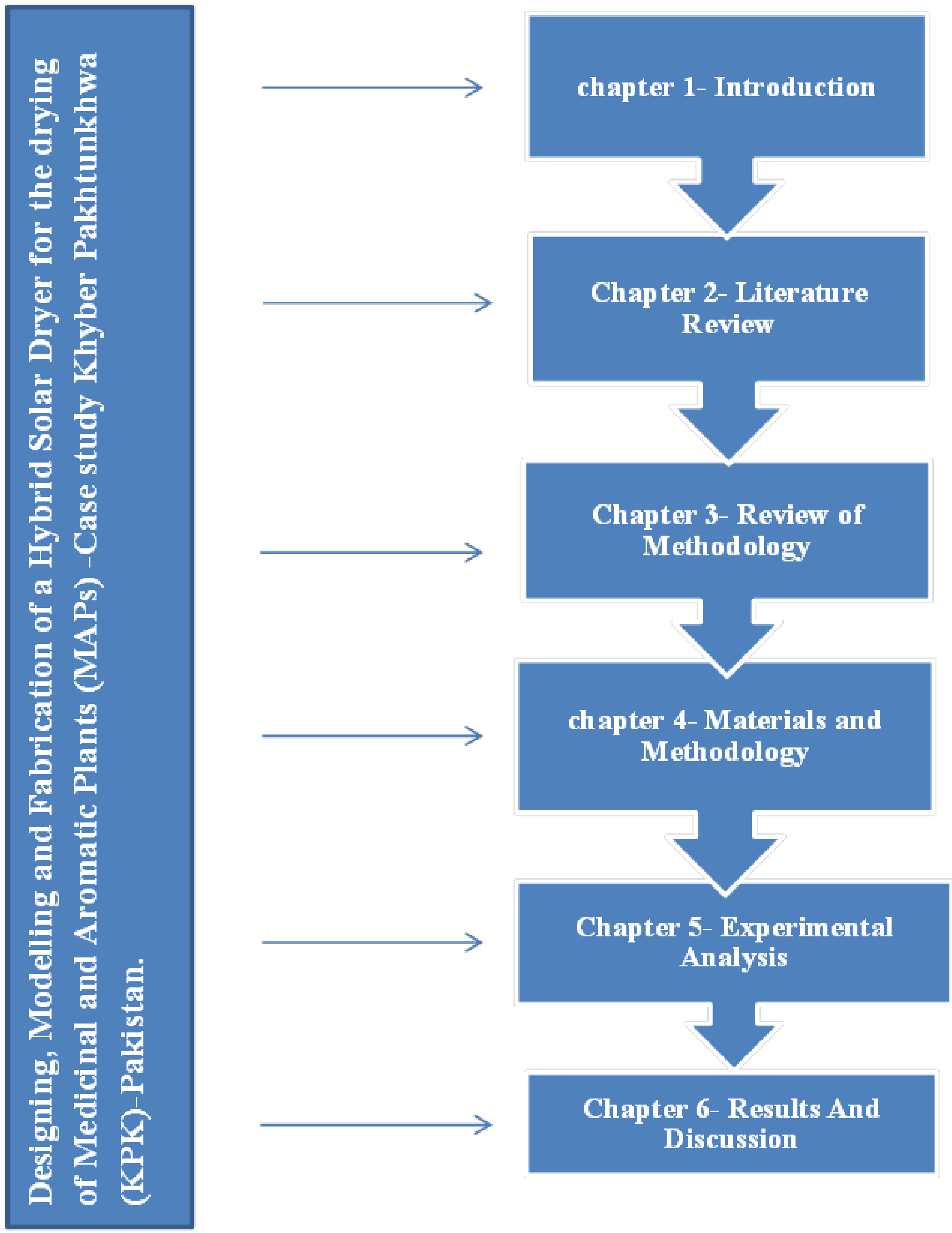

Figure 1.1: Thesis Layout

Summary

Medicinal plants possess definite pharmacological attributes due to the presence of active chemical constituents in different parts like roots, stems, fruits or leaves. And thus cure various ailments in human body. Use of medicinal plants and herbs to cure diseases and heal physical sufferings, dates back to earliest centuries. But the lack of awareness on the part of collectors, unsustainable harvesting, dearth of modern post-harvest operations like drying, extraction, purification, packaging and restricted market access are some of the tailbacks for the emergence of herbal industry in developing countries. Pakistan has over 6000 species of high-economic value plants. 600 to 700 species are used for medicinal, aromatic and cosmetic purposes. Upper highlands like SWAT, SHANGLA and DIR valley are blessed with rich flora of MAPs. There is dire need to harness these resources on sustainable basis to conserve this valuable resource and to the uplift the socio-economic conditions of the area. Pakistan has immense potential of solar energy and this source is abundantly available all across the country. Thus solar thermal energy can find potential applications in drying of agricultural products and medicinal plants by using solar dryers. But Open sun drying is common practice for preservation of herbs. It is economical, but it results in quality deterioration, unpredictable drying time, and fungus growth in the dried products during cloudy/rainy conditions. Thus lack of modern post-harvest techniques like efficient, clean and economical drying is resulting in quality deterioration of herbs, limiting the financial returns to collectors. This study is aimed at designing a biomass hybrid solar dryer to ensure clean, efficient, continuous and economical drying of herbs in northern areas of Pakistan which have an adequate solar potential.

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CHAPTER 2

LITERATURE REVIEW

Rapid industrialization, urban sprawl, and swift economic growth are chief driving factors for increased energy demand worldwide. Fossil fuels are prime energy source in global energy mix. But the detrimental environmental impacts and restricted supplies of fossil fuels have resulted in concerns of energy security for developing countries particularly. Thus there is dire need to harness enormous renewable energy potential that we are blessed with.

Solar thermal is the most abundant among all renewable energy sources. Sun the gigantic energy source radiates energy at the rate of $3.8*10^{23}$ kW, out of which $1.8*10^{14}$ kW is intercepted by our planet earth. After reflection into space and atmospheric scattering, about $1.08*10^{14}$ makes its way to the earth surface. If only 0.1% of this massive source is converted at 10% efficiency, it will generate four times more the world total generation capacity of 3000 GW [1].

Hence solar energy is considered as the most attractive sustainable energy option. And in near future large scale deployment of solar thermal energy can be anticipated worldwide. On the other hand intermittent nature of solar energy and reliance on meteorological conditions are major impeding factors for its ample exploitation. Thus energy storage is indispensable for large scale utilization of solar energy [2],[3].

Solar drying of agricultural products, herbs and medicinal plants, is one of the potential applications of solar thermal energy in developing countries particularly. However, very little research has been conducted in this field. Open sun drying involves the direct exposure to solar radiation, while in solar drying; radiations are trapped by the use of equipment (solar dryer) for drying purposes [4].

Figure 2.1 describes the Principal of open sun drying. Some of the short wave solar radiations, intercepted on product surface are reflected back, while remaining radiations are absorbed by the surface. Due to this absorbed thermal energy temperature of the product start rising. This temperature gradient results in long wavelength radiation loss from product surface to ambient air. Wind gusts over the material surface also result in convective heat losses.

First top layer of the product gets dry through moisture evaporation; further absorbed thermal energy is conducted into the inner layers of the product. This results in temperature rise and subsequent vaporization inside the material. These vapors diffuse towards the surface then, and finally lose energy to the ambient air. Moisture removal from the top surface is rapid due to surplus moisture on the surface, but further drying inside the material is slow comparatively. This is due to the entrapped moisture within interior layers of product. Thus drying rate now depends on diffusion rate of this moisture towards the top surface [5].

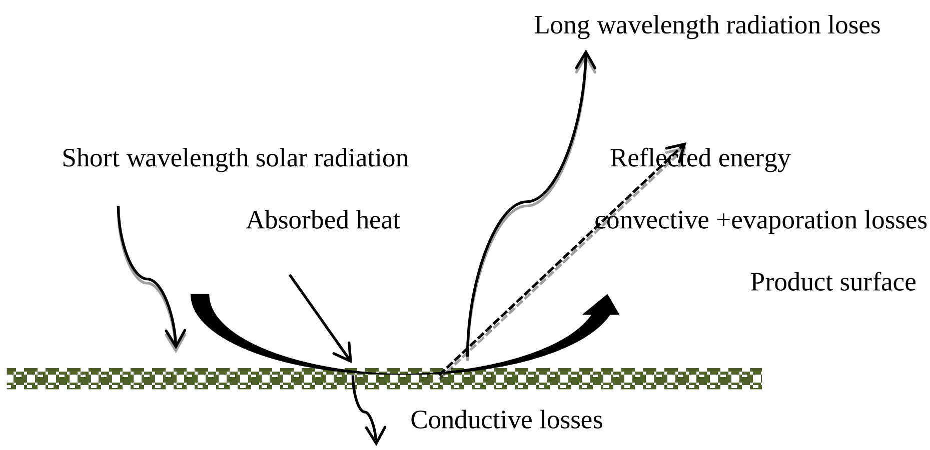

Figure 2.1: Open Sun Drying Mechanism

In developing countries open sun drying is the most common method for drying of herbs and agricultural products. Although this is cost effective method, but products dried are often unhygienic due to contamination by birds, insects and dust. Other major pitfalls include weather dependence, rewetting of products by rain, intermittent drying process and unpredictable drying time. High air humidity in rainy season favors the mold development and microbial activity in pants, as a result dried products often contain toxics like Alphatoxil produced by molds.[6].

Hence solar dyer is vital to overcome these problems of sun drying, as it traps the radiative heat judiciously and ensures the product quality [2]. Solar dryer accelerates the drying process by supplying more heat, which results in increased vapor pressure of product moisture content and decreased relative humidity of air, which in turn increases the moisture loading capacity of air. In this way solar dryer ensures efficient drying mechanism [5].

2.1 Classification of Drying Systems

Categorization of drying systems based on operating temperature and heating source is as follows:

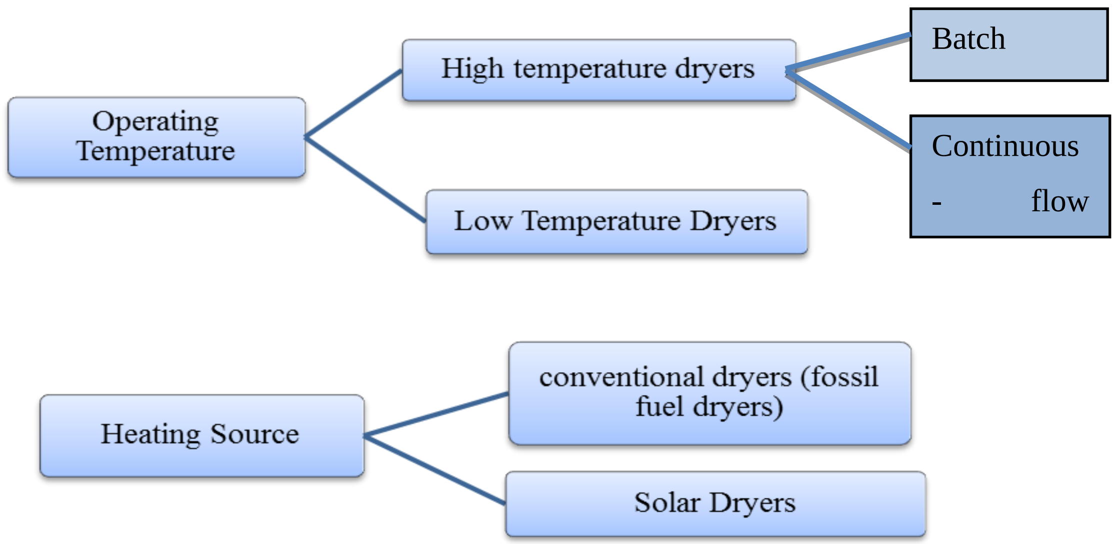

Figure: 2.2 Classification of drying systems

2.1.1 High Temperature Dryer

These are employed for rapid drying, when products need very short exposure with the hot air, to attain equilibrium moisture content. Their operating temperature is too high that prolong contact with drying air results in over dried products. These are further classified into batch and continuous flow dryers. In batch dryers, products are first dried in a bin and then moved to storage box, and proceeds to the next batch. In continuous flow dryers products are exposed to hot air while descending under gravity, through heated columns. Owing to high temperature range required, most of these designs are electrical or fossil fuels powered.

2.1.2 Low Temperature Dryer

In low temperature dryers, products are dried up to equilibrium moisture content by constant ventilation of drying air. Due to low temperature, these systems can adjust variable heat supply without affecting the product quality. These dryers are more suitable for bulk drying. Such dryers are most applicable for solar energy applications as they can tolerate intermittent heat supply.[5].

2.2 Type of Solar Dryers

On the basis of heating mode, solar dryers are classified as active and passive dryers. Further there are two sub-categories of either active or passive dryers based on mode of employment of solar heat, these categories also differ in system design.

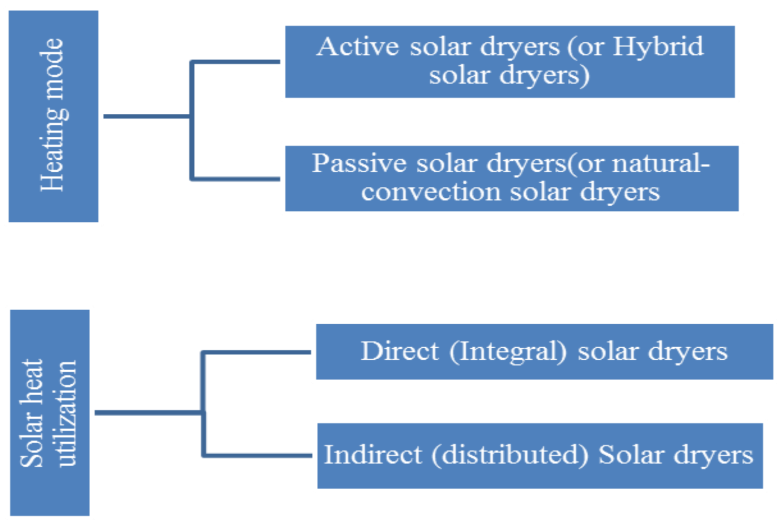

Figure 2.3: Classifications of solar dryers

In direct solar dryers products are directly exposed to the solar radiation. Incident solar energy heats the product as well as the internal walls of the drying chamber. While in indirect solar dryers products are not directly exposed to the solar radiation, instead hot air from solar collector is ducted to the drying enclosure. These are less compact as compared to direct solar dryers, but more efficient [4].

2.2.1 Direct Solar Dryer

Direct solar dryers employ only natural flow of hot air. Glass cover of the dryer chamber reflects back a part of incident solar rays and remaining is transmitted inside the chamber. Products inside the chamber absorb a part of transmitted radiation and reflect back the remaining energy. Further the drying mechanism of product is same as described in open sun drying. But here the glass cover does not allow long wavelength radiation emitted by the product to escape to ambient. Thus temperature inside the chamber increases.

Glass cover also reduces the convective losses to the ambient which increases the product and chamber temperature. Inlet air from bottom of the chamber carries away moisture from product surface and exits through top opening of the chamber. [1]described a simple natural convection cabinet dryer, which consists of an insulated dryer chamber with perforated drying trays inside and air holes on sides of the chamber. Drying chamber is covered with transparent glass or plastic.

Some researchers reported a modified and more efficient design of cabinet dryer. This was furnished with a wooden plenum to serve as an air inlet to the drying chamber, and also had a long chimney to improve air circulation [5].

2.2.2 Indirect Solar Dryers

In these dryers, products are not exposed to direct solar radiation, to protect them from discoloration and to preserve active ingredients. So indirect solar dryers are particularly used to dry herbs and medicinal plants.

2.2.3 Reverse Absorber Cabinet Dryer (RACD)

Reverse absorber cabinet dryer (RACD) comprises of a cylindrical reflector and absorber. Absorber is fixed below the drying chamber, with enough space between the absorber and chamber to serve as air channel. Reflector with a glass cover on its aperture is fitted below the absorber. Glass cover transmits solar radiation towards the reflector, which then reflects towards the absorber. A part of this absorbed energy is lost to ambient, and remaining is transferred to the flowing air by convection. Heated air then passes through the drying trays placed in chamber above, and exits through a vent at the top of chamber (Fig.2.4)[5].

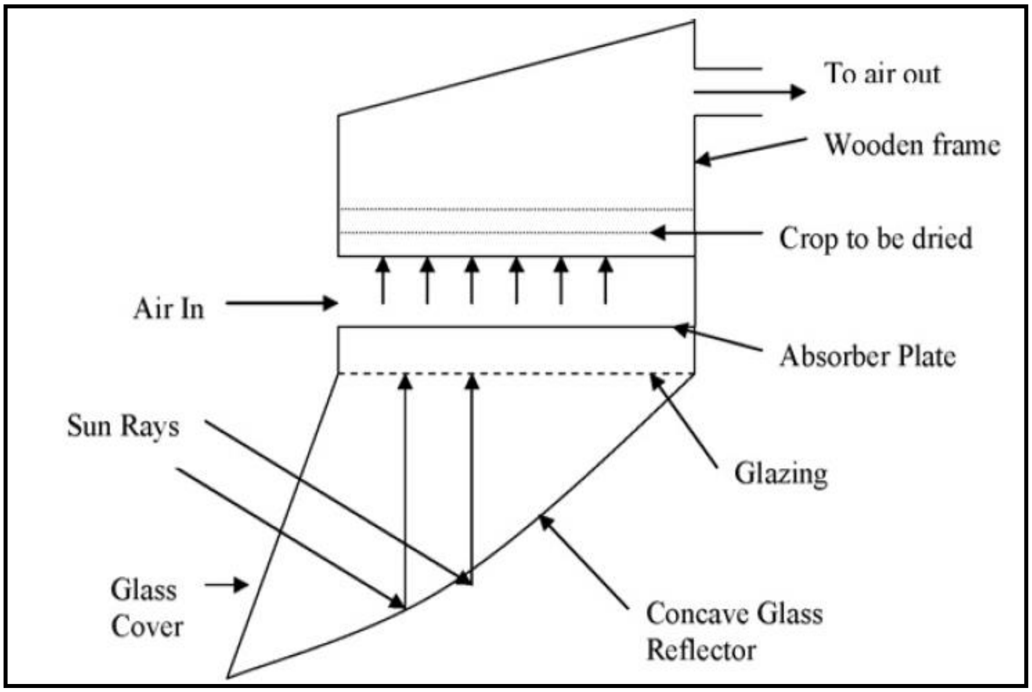

Figure 2.4: Reverse Absorber Cabinet Dryer

Forced Convection Solar Dryer

In this type of dryers, solar air heaters/ collectors are employed to heat the inlet air; hot air is then ducted to the drying chamber. Hot air flowing through the wet material picks up moisture and exits through the exhaust vent (Fig.2.5). Drying rate depends on the moisture gradient between drying air and air around the product surface: greater the moisture gradient higher is the drying rate. These dryers offer better control over drying process and maintain the product quality [2].

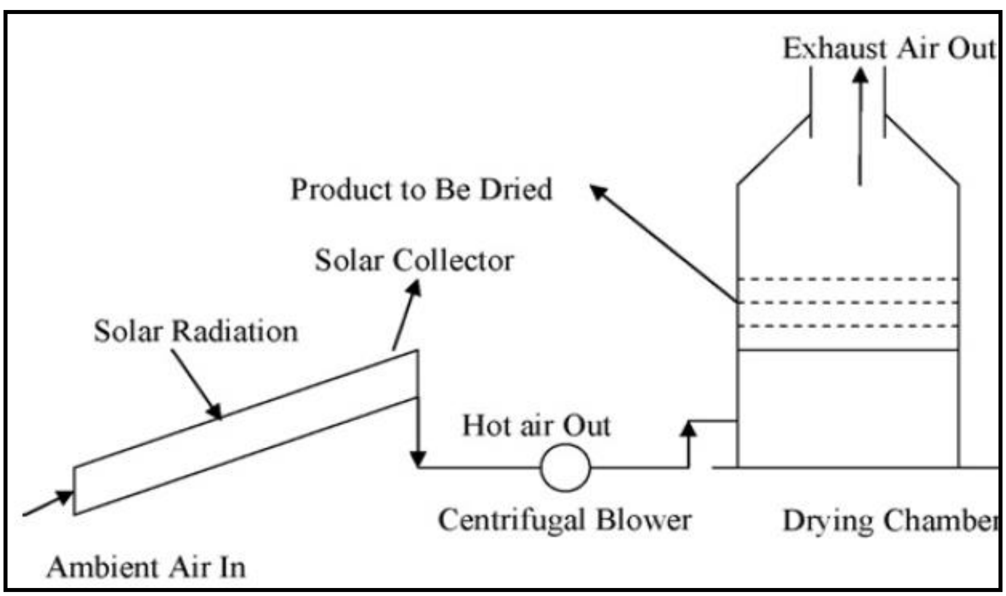

Figure 2.5: Forced Convection Indirect Solar Dryer

Green House Solar Dryer

Green house dryers are most appropriate for dying in rural area as they are simple in design and operation as well. Here incident short wavelength radiations penetrates through glass or polycarbonate cover, temperature of the inside cover and product increases, as a result long wavelength radiation are emitted. But these radiations are trapped inside the cover by what is known as “greenhouse effect”. Hence temperature further increases. But such systems have one major drawback: its vulnerability to damage by high speed wind [5].

Solar Tunnel Dryer

Tunnel dryer consists of a solar collector and drying unit, both are connected in series in the form of tunnel, and covered with UV stabilized plastic sheet. The required air flow rate is provided by exhaust fans which can be operated by PV panel. The whole system is supported horizontally on a platform (Fig 2.6). Unlike other dryers, in solar tunnel dryer air is passed over the products rather than through the products, so required air flow rate and fan power is very low.

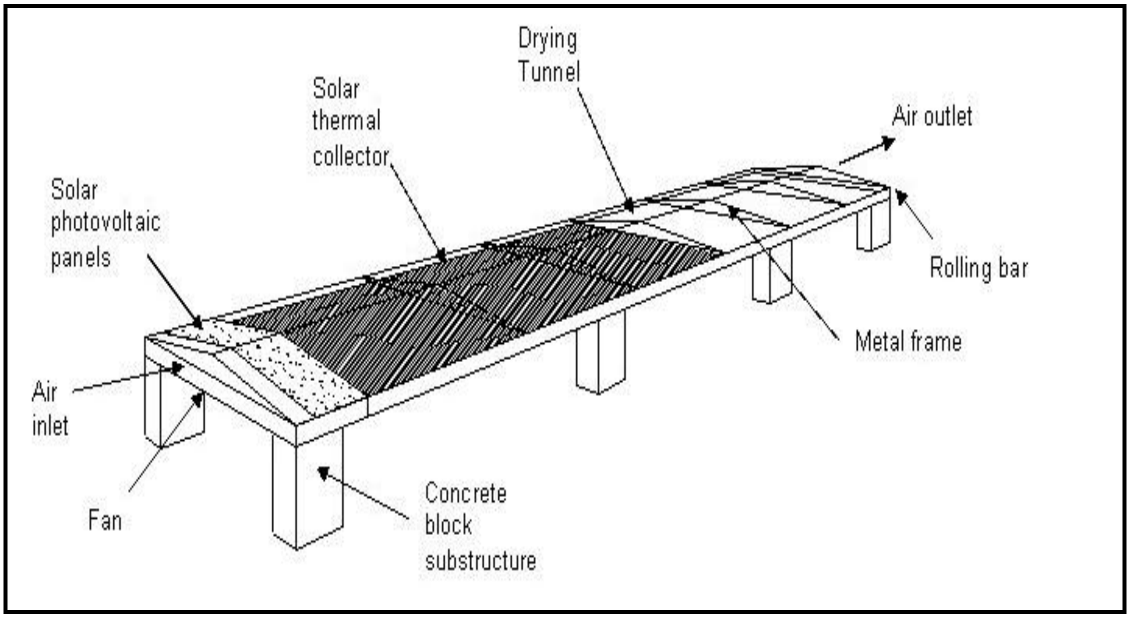

Figure 2.6: Solar Tunnel Dryer

In addition to these, many other dryers have been developed with some modifications, according to drying requirement and technology available.

2.3 Experimental Analysis of Different Types of Solar Dryers

Thermal performance of an indirect-mode forced convection solar dryer was investigated, under ambient conditions of Tanta, Egypt. The system consisted of a double pass V-corrugated flat plate solar air collector, drying chamber and a blower to force the hot air to drying chamber. The dryer was tested under ambient temperature for drying Thymus (initial M.C 95% on wet basis) and Mint (initial M.C 85% on wet basis). Under drying temperature of 39-54^{O} C' thymus attained final M.C of 11% after 34 hours, while mint leaves reached up to same M.C after 5 hours. With local available material, total drying cost of thymus and mint in indirect-mode forced convection solar dryer was 0.087 €/kg and 0.025 €/kg, respectively[7].

Janjai and Tung [2005] developed a solar dryer for drying herbs and spices, and tested under ambient conditions of Thailand. Hot air is supplied to the drying chamber from roof integrated solar collectors through ducts and air distribution box. North and south facing collectors also serve as the roof of a farm house (Fig.2.7). This dryer has the capacity to dry 200kg of rosella flowers and lemon grasses within 4 and 3 days, respectively. And the solar collectors have average efficiency of 35% [8].

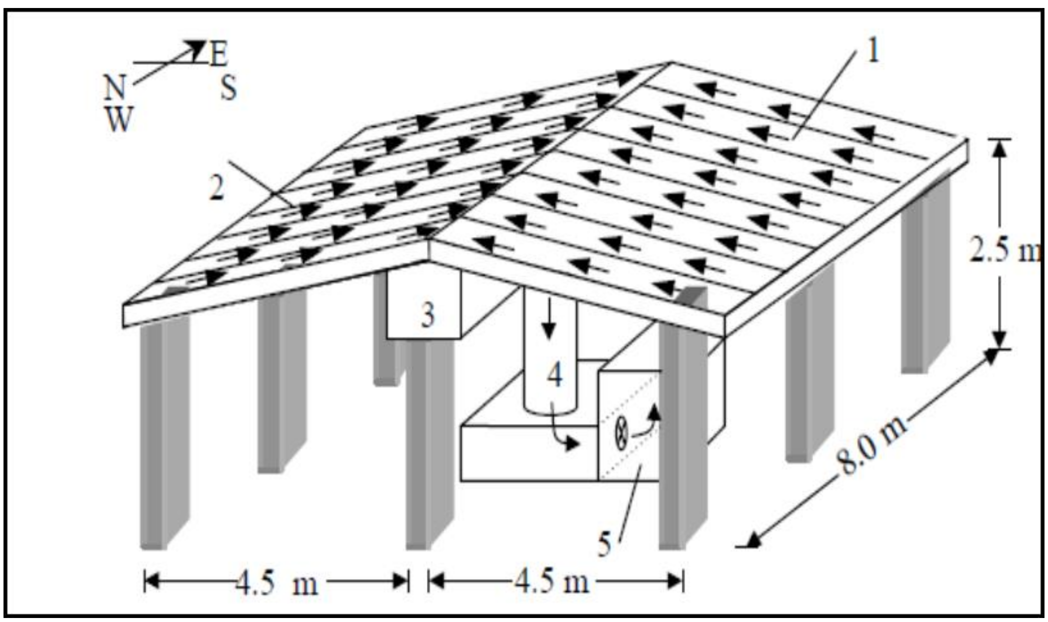

Figure 2.7: Schematic Diagram of solar Dryer with Roof-Integrated Solar Collectors: (1)south-facing collectors,(2)north-facing collectors,(3)horizontal air duct,(4)vertical air duct,(5)dryer

A passive solar dryer with phase change material (PCM) as heat storage system has also been developed and investigated. The system consists of a glazed flat plate solar collector with PCM modules across the absorber plate. The spaces between equally spaced modules provide the air heating channels; hot air enters the drying chamber through discharge headers. Thermal performance of the system was studied under no load conditions, at Nsukka, Nigeria. Under ambient temperature of 19-41^{0}C and global radiation of 4.9-19.9 MJ/m^2, air temperature rise was about 15K above the ambient, with peak overall system efficiency of 22%.[9]

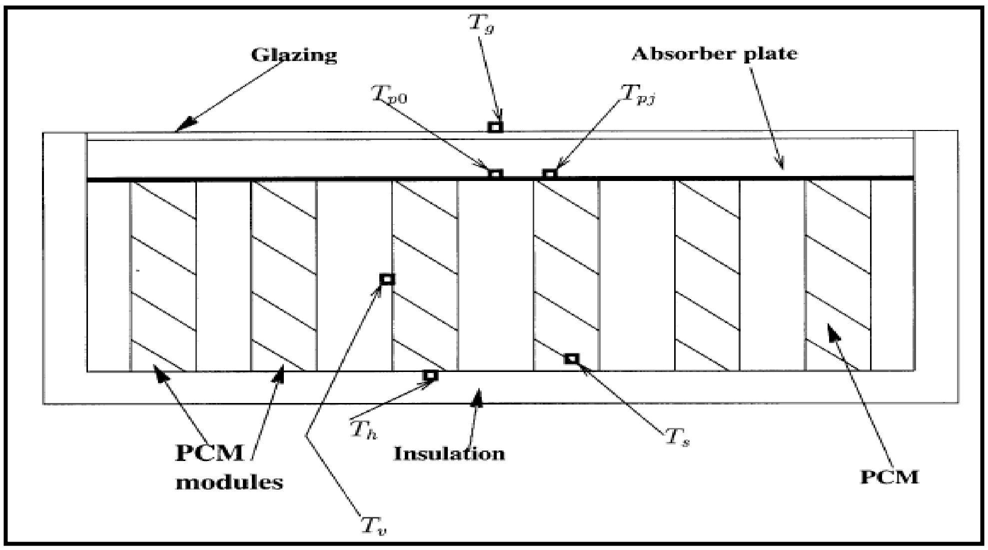

Figure 2.8: Cross-Sectional View of Solar Collector with PCM modules

Many Thai herbs are used as traditional medicines and drying is the first step in product preservation. In Thailand, an indirect, natural convection hybrid solar dryer with biomass burner has been designed. The system was also integrated with thermal storage unit made of bricks, to store heat from wood combustion. Solar collector was used to heat the ambient air during sunny hours while biomass burner supplied heat during night time. Thermal performance of the solar dryer was tested with the Thai herb, *Rhinacanthus nasutus* (Linn.) Kurz, results demonstrated uniform drying of herb and temperature inside the drying chamber was maintained at 50^{o}C. Thermal efficiency of the solar dryer using solar energy was 10.5% but less than 1% when dependent on biomass burning [10].

A direct type, natural convection solar-biomass hybrid dryer and compared the drying behavior of Zingiber officinale (Ginger) under open sun drying and solar dryer has been designed in Delhi, India. The dryer consists of a drying cabinet riding over a brick chamber, which encloses the biomass burner. The glass cover inclined on the cabinet top directs the solar radiation towards the drying trays. Brick chamber has three metallic baffles inserted above the grate and below the exhaust exit; these baffles lengthen the flow path of exhaust gases and maximize the heat transfer to the burner wall (Figure 2.9)

Drying experiments indicated that solar dryer preserves the product quality: loss of volatile oil content of the product is much less as compared to open sun drying. And solar-biomass hybrid dryer increases the drying potential of air and drying rate as well. The overall drying efficiency of the system was found to be 18% and 13% under summer and winter conditions, respectively [11].

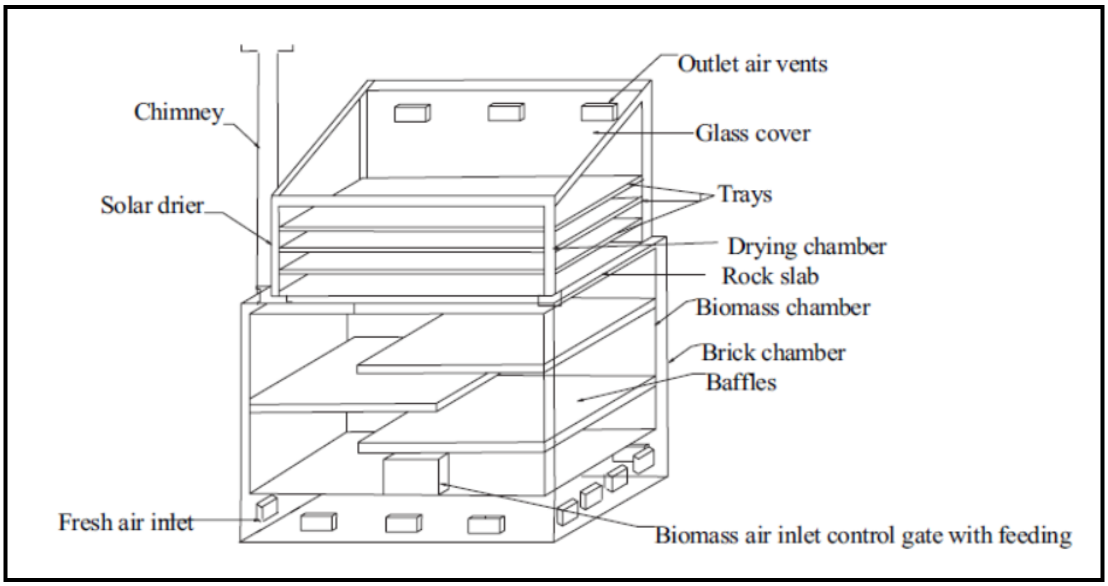

Figure 2.9: Schematic View of Solar Biomass Dryer

A large-scale solar greenhouse dryer with drying capacity of 1000 kg fruits or vegetables has been investigated in Lao People's Democratic Republic (Lao PDR). The dryer has parabolic shape to withstand wind gusts and it is covered with polycarbonate sheets. And concrete floor which is painted black serves as the base of dryer. For air ventilation, DC fans are used, which are powered by PV module.

To assess the thermal performance of dryer, drying tests were conducted for drying chilli, banana and coffee under the ambient conditions of Lao People's Democratic Republic

(Lao PDR). Drying time for one thousand kg of banana with initial M.C of 68% was 5 days, and for 300 kg of chilli with initial M.C of 75 % was 3 days, and for 200 kg of coffee with initial M.C of 52% was 2 days [12].

A cabinet solar dryer made of fiber reinforced plastic (FRP) for drying of medicinal plants in arid areas was designed. After theoretical modeling, thermal performance of solar dryer was evaluated experimentally using shrinkage factor. The drying results demonstrated constant heat transfer coefficient for drying materials of thickness between 2mm and 10mm, and no effect on materials of less than 2mm thickness. High heat capacity materials (HHCM) like blackened stones and pebbles and PCM ($NaOH.H_2O$) were used to control the heat transfer coefficient, so that color of drying material can be preserved [13].

An indirect solar dryer with PCM (phase change material) as energy storage medium has been designed in Egypt. The system was investigated under no load conditions at varying flow rates (0.0664–0.2182 kg/s) in Tanta, Egypt. The system with PCM was capable to maintain the air temperature 2.5-7.5^{o}C above ambient for five hours after sunset. And highest air temperature was achieved with flow rate of 0.12kg/s when using PCM, and 0.0894 kg/s without using PCM [14].

Summary

Solar drying systems are classified on the basis of mode of heating (active or passive dryers), solar heat utilization (direct or indirect dryers). Worldwide different types of solar dryers like greenhouse dryer, tunnel dryer, Transpired Collector Type Solar Dryer etc., have been designed and tested experimentally. Experimental analysis proves that thermal efficiency of the dryer depends upon design, mode of convection and ambient conditions also. Indirect solar drying system is more efficient as drying products are protected from direct exposure to intense solar radiation. Forced convection solar drying system provides more efficient and rapid drying than natural convection drying system. Although greenhouse dryers have higher loading capacity but average drying temperature in tunnel and greenhouse dryers is comparatively low; this is due to high heat losses to ambient. Drying temperature is critical parameter as it directly influences the active ingredients within herbs. Literature study concludes that optimum drying temperature for drying of medicinal plants is 50-60^oC. Most solar drying systems have been designed for fruits and vegetable drying, but no significant research has been done for drying of herbs and medicinal plants in Pakistan, particularly.

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CHAPTER 3

REVIEW OF METHODOLOGY

3.1 Herbs Drying

Solar thermal energy is the most abundant among all renewable energy sources and the most attractive sustainable energy option. On the other hand intermittent nature of solar energy and reliance on meteorological conditions are major impeding factors for its ample exploitation. Thus energy storage is indispensable for large scale utilization of solar energy [1], [2],[3].

Solar drying of agricultural products, herbs and medicinal plants, is one of the potential applications of solar thermal energy in developing countries particularly. However, very little research has been conducted in this field. Open sun drying involves the direct exposure to solar radiation, while in solar drying; radiations are trapped by the use of equipment (solar dryer) for drying purposes [4].

In developing countries open sun drying is the most common method for drying of herbs and agricultural products. Although this is cost effective method, but products dried are often unhygienic due to contamination by birds, insects and dust. Other major pitfalls include weather dependence, rewetting of products by rain, intermittent drying process and unpredictable drying time[5].

Hence solar dyer is vital to overcome these problems of sun drying, as it traps the radiative heat judiciously and ensures the product quality [2]

3.2 Solar Dryer Technology Overview

Worldwide different types of solar dryers like greenhouse dryer, tunnel dryer, Transpired Collector Type Solar Dryer etc., have been designed and tested experimentally. Thermal efficiency of the dryer depends upon design, mode of convection and ambient conditions also. However, forced convection solar drying system provides more efficient and rapid drying than natural convection drying system. Following is the performance overview of different types of solar dryers.

A novel indirect solar dryer Implementing PCM as energy storage medium was experimentally investigated in Egypt, under no load condition. The system was able to maintain air temperature 2.5-7.5 C^o higher than ambient, for 5 hours after sunset. And peak temperature rise with air flow rate 0.12kg/s.[6]

Experimental Investigation of an indirect-mode forced convection solar dryer was done in Egypt, for drying Thymus and Mint. Average moisture removal efficiency was 87% and maximum drying temperature achieved was 39-54^{o}C [7]. Solar cabinet dryers have also been designed for drying different agricultural products and herbs in Turkey. Experimental analysis proved that such dryers can achieve average drying temperature up to 52 ^{o}C with overall drying efficiency of 10% [2].

A large-scale solar greenhouse dryer with drying capacity of 1000 kg fruits or vegetables has been developed in Lao People's Democratic Republic (Lao PDR). To assess the thermal performance of dryer, drying tests were conducted for drying chilli, banana and coffee under the ambient conditions of Lao People's Democratic Republic (Lao PDR). Average moisture removal efficiency was found to be 60% [8].

Unglazed transpired collector type solar dryer for repining and drying of dates was designed in Dera Ismail Khan, KPK-Pakistan. Moisture removal efficiency was 45%, Collector efficiency: 50 to 80%. And Temperature rise was 50 to 60^{o}C at ambient 35-40^{o}C (S.Hussain, et al. 2010). A PV-ventilated solar greenhouse dryer was tested in Thiland, for drying peeled longan and banana. Average Moisture removal efficiency was 75% with average drying air temperature of 30-58^{o}C[8].

Drying Characteristics of *Zingiber Officinale* (Ginger) were studied under open sun and solar biomass (Hybrid) Drying in Delhi, India. Field tests indicates the overall drying efficiency of the hybrid drier is 18% and 13% (under summer and winter climatic conditions respectively), with average drying air temperature of 60^{o}C[9].

A solar dryer using hot air from roof-integrated solar collectors has been developed, for drying herbs and spices with drying capacity of 200kg. Experiments revealed the average Moisture removal efficiency of 70% and average daily solar collector efficiency of 35% [10].

3.3 Optimum Drying Temperature

Drying temperature is the most important parameter to preserve the active ingredients of volatile oils, as it has direct influence on the quality of dried products. Drying is the most common and fundamental method for post-harvest preservation of herbs. Drying process represents 30 -50% of the total costs in medicinal plant production [11].

Drying temperature is critical factor for the preservation of active ingredients within herbs. Too high temperature (above 60^{o}C) results in loss of essential oils, thus deteriorates the quality of MAPs, while too low temperature (below 50^{o}C) results in accelerated decomposition by promoting enzyme activity within herbs. Thus optimum drying temperature is critical to get the final dried products of international quality standards. The values recommended in literature differ greatly from that in practice. However, drying temperature between 50-60^{o}C is considered as optimum drying temperature[12].

Summary

This chapter presents a review of different types of solar dryers that have been designed and tested worldwide. This chapter also summarizes the thermal performances of different dryers. Worldwide different types of solar dryers like greenhouse dryer, tunnel dryer, Transpired Collector Type Solar Dryer etc., have been designed and tested experimentally. Thermal efficiency of the dryer depends upon design, mode of convection and ambient conditions also. Forced convection solar drying system provides more efficient and rapid drying than natural convection drying system. Drying temperature is critical parameter as it directly influences the active ingredients within herbs. Literature study concludes that optimum drying temperature for drying of medicinal plants is 50-60^{o}C. Most solar drying systems have been designed for fruits and vegetable drying, but no significant research has been done for drying of herbs and medicinal plants particularly.

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CHAPTER 4

MATERIALS AND METHODOLOGY

This chapter deals with methodology and procedures to develop an indirect-mode forced convection hybrid solar dryer model. First section deals with the mathematical modeling and simulation of different components of solar dryer. Based on mathematical modeling and simulation results, lab scale prototype of solar dryer has been fabricated at Manufacturing Resource Center (MRC) at NUST, using locally available materials and technology.

4.1 Study of Design Parameters of Solar Dryer

4.1.1 Drying Temperature

Drying temperature is critical factor for the preservation of active ingredients within herbs. Too high temperature (above 60^{o}C) results in loss of essential oils, thus deteriorates the quality of MAPs, while too low temperature (below 50^{o}C) results in accelerated decomposition by promoting enzyme activity within herbs. Thus optimum drying temperature is critical to get the final dried products of international quality standards. The values recommended in literature differ greatly from that in practice. However, drying temperature between 50-60^{o}C is considered as optimum drying temperature [1]

Table 4.1: Moisture Content of MAPs

Botanical name	Local name	Recommended final Moisture content (%)
Biostorta amplexicaulis	Anjabar	Less than 15
Valariana jatamansi	Mushk bala	Less than 15
Viola Spp (flowers)	Banafsha	Less than 10
Hypericum perforatum	Shna chai	Less than 10
Urticadioica	Jal Bang	Less than 10
Dioscoreadeltoidea	Kanis	Less than 15

4.1.2 Final Equilibrium Moisture Content

Initial moisture content varies from specie to specie, but final or equilibrium moisture content is from 10-15% for most of the medicinal plant species. Final moisture content for some of the species is shown below:

Lab Scale Prototype of Solar Dryer

Lab scale prototype of solar dryer consists of a flat plate solar collector, drying chamber, biomass burner, heat exchanger, temperature sensors and two DC fans. Biomass burner serves as the supplement heat source in case of rainy or cloudy weather. And fans force the hot air from solar collector or biomass burner to the drying chamber, at required flow rate. Hot air moves through perforated trays inside the drying chamber from bottom inlets, and absorbs moisture from the products. Then relatively cold and moist air exits through the top vent.

4.2 Mathematical Modelling and Simulation

This section presents the mathematical model and simulation algorithms for various components of the lab scale prototype of solar dryer.

4.2.1 Flat Plate Solar Air Collector

Solar air heaters employ solar radiation to heat air for many processes that involve low to medium temperature below 80^{o}C like crop drying and air conditioning [2]. Flat plate collectors consist of a top glass cover to transmit solar radiation towards the absorber plate that converts absorbed energy to heat, so increasing the enthalpy of air that flows through the air channel between absorber and cover, and bottom insulation to eradicate heat losses [3].

Basic flat plate collector consists of following main elements:

Transparent cover (glazing) To ensure maximum transmission of incoming solar radiation, glazing material should have high transmissivity (τ), high temperature stability, low absorptivity (α) and low reflection. Low iron content tempered glass is the most common glazing material for solar collectors as it has maximum transmissivity (0.85 - 0.90 at normal incidence) for incoming short wave radiation, but almost zero transmissivity for long wave radiation emitted by the absorber.

Absorber Its prime function is to absorb maximum light transmitted through glazing, so to transfer the retained heat to the circulating fluid (water or air) with minimum losses to the surroundings. Most common materials used as absorber are copper and aluminum. Usually absorber plates are coated with selective coatings (for which α=0.92-0.98) to enhance their absorptivity.

Insulation Flat plate collectors are insulated to minimize the conduction and convection losses from the bottom and edges of collector. Usually mineral wool, rock wool and glass wool are used as insulation[4].

4.2.2 Mathematical Model of Flat Plate Solar Air Collector

Main losses from flat plate solar air collectors are optical and thermal losses. Optical losses are caused by reflection and absorption by transparent cover or due to less absorptivity of the absorber. While thermal losses are mainly caused by convection and conduction [34]. Flat plate solar collector with single air channel between top cover and absorber plate is being considered here for thermal analysis and development of a mathematical model. [5],[6]

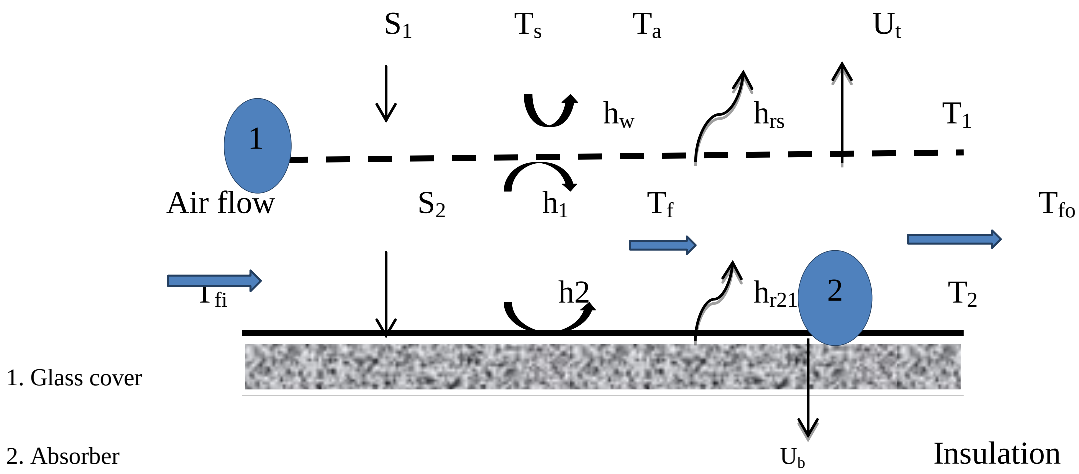


Figure 4.1: Flat Plat Solar Air Collector- Thermal Analysis

Radiation Heat Transfer

The radiation heat transfer coefficient from top cover to the sky is calculated as:

$$h_{rs}= \sigma\times\epsilon_1 (T_1+T_s)(T_1^2+T_s^2)(T_1-T_s)/(T_1-T_a) \qquad (4.1)$$

When $T_a = T_s$ equation (1) becomes

$$h_{rs}= \sigma\times\epsilon_1 (T_1+T_s)(T_1^2+T_s^2) \qquad (4.2)$$

Radiation heat transfer between cover and absorber (1 and 2) is:

$$h_{r21}= (\sigma \times (T_1^2+T_2^2)(T_1+T_2)) / (1/\epsilon_1+1/\epsilon_2 -1) \qquad (4.3)$$

Convection Heat Transfer Due To Wind

Convection heat transfer coefficient from top cover due to wind is:

$$h_w = 5.7+ (3.8) \times V \qquad (4.4)$$

Where V is wind speed.

Forced Convection Heat Transfer between Cover And Absorber

Air flow between cover and absorber can be laminar, transition or turbulent, which can be determined from Reynolds number (Re).

$$Re= (\dot{m}\times D_h)/(A\times\mu) \qquad (4.5)$$

Laminar flow: if Re is < 2300, air flow is laminar. Nusselt number is then calculated as

$$Nu=Nu_{infinity}+(Nu_1)/(Nu_2). \qquad (4.6)$$

Where

$Nu_1= a\times [Re\times P_r\times(D_h/L)]^{m}$, $Nu_2=1+b\times[Re\times P_r\times(D_h/L)]^{n}$

And constants are:

a=0.0019; b=0.00563; m=1.71; n=1.17; $Nu_{infinity}$=5.4(for P_r = 0.7)

Turbulent Flow If Re is > 6000, air flow is turbulent. Nusselt number is calculated as:

$$Nu=0.023\times Re^{0.8}\times [Pr^{0.4}] \qquad (4.7)$$

Transition flow if 2300< Re<6000 then air flow is in transition region. Nusselt number is calculated as:

$$Nu= 0.116 \times (Re^{0.68}-125) \times (P_r^{0.33}) \times(1+ (D_h/L)^{0.68}) \qquad (4.8)$$

Based on Nusselt number calculated as above (which ever case applies) convection heat transfer coefficient is calculated as:

$$h=Nu\times K/D_h \qquad (4.9)$$

Where D_h is hydraulic diameter.

It is assumed that convection heat transfer coefficient from cover to air (h_1) and from absorber plate to air stream (h_2), both are equal. Thus

$$h_1=h_2=h$$

Solar Radiation

Solar radiation flux absorbed by top cover is:

$$S_1 = \alpha_1\times H \qquad (4.10)$$

And by absorber plate:

$$S_2=\tau\times\alpha_2\times H \qquad (4.11)$$

Overall Heat Loss Coefficients

Overall heat loss coefficient from top surface is:

$$U_t= h_w + h_{rs} \qquad (4.12)$$

And for bottom heat loss:

$$U_b = 1/ [(x_{bi}/ k_{bi}) + (1/h_w)] \qquad (4.13)$$

4.2.3 Simulation Procedure for Flat Plate Solar Collector

The theoretical model assumes that:

a) Temperature of the walls (cover and absorber) surrounding the air stream are constant for a short collector.
b) Heat losses from collector edges are negligible.
c) Properties of collector material (cover, absorber and insulation) are independent of temperature.
d) Uniform mass flow rate ($\dot{m}$) in the air channel of collector.

Simulation algorithm in MATLAB software has been developed to calculate the cover temperature, absorber and mean air temperature at collector outlet for each hour of the day. For first hour wall and mean air temperatures are assumed equal to the ambient temperature, and heat transfer coefficients are calculated by using above equations. Then following matrix is developed:

$$\begin{bmatrix} (h_1 + h_{r21} + U_t) & -h_1 & -h_{r21} \\ h_1 & -(h_1 + h_2 + z) & h_2 \\ -h_{r21} & -h_2 & (h_2 + h_{r21} + U_b) \end{bmatrix} \begin{bmatrix} T_1 \\ T_{fo} \\ T_2 \end{bmatrix} = \begin{bmatrix} U_t T_a + S_1 \\ -(z * T_{fi}) \\ S_2 + U_b T_a \end{bmatrix}$$

Where $z = 2\dot{m}C/WL$

It can be written as: $[A]\,[T] = [B]$ (4.14)

Here mean temperatures [T] is calculated by using matrix inversion method in MATLAB. In this way mean temperatures of all hours in a day or a month can be predicted for given collector. MATLAB algorithm is shown in a flow chart below. To predict the mean temperatures for a flat plate solar air collector, simulation was performed for a short collector length. Ambient conditions for ISLAMBAD, PAKISTAN were reported from METEONORM global meteorological database. However this simulation procedure can be used for any ambient conditions and collector specifications.

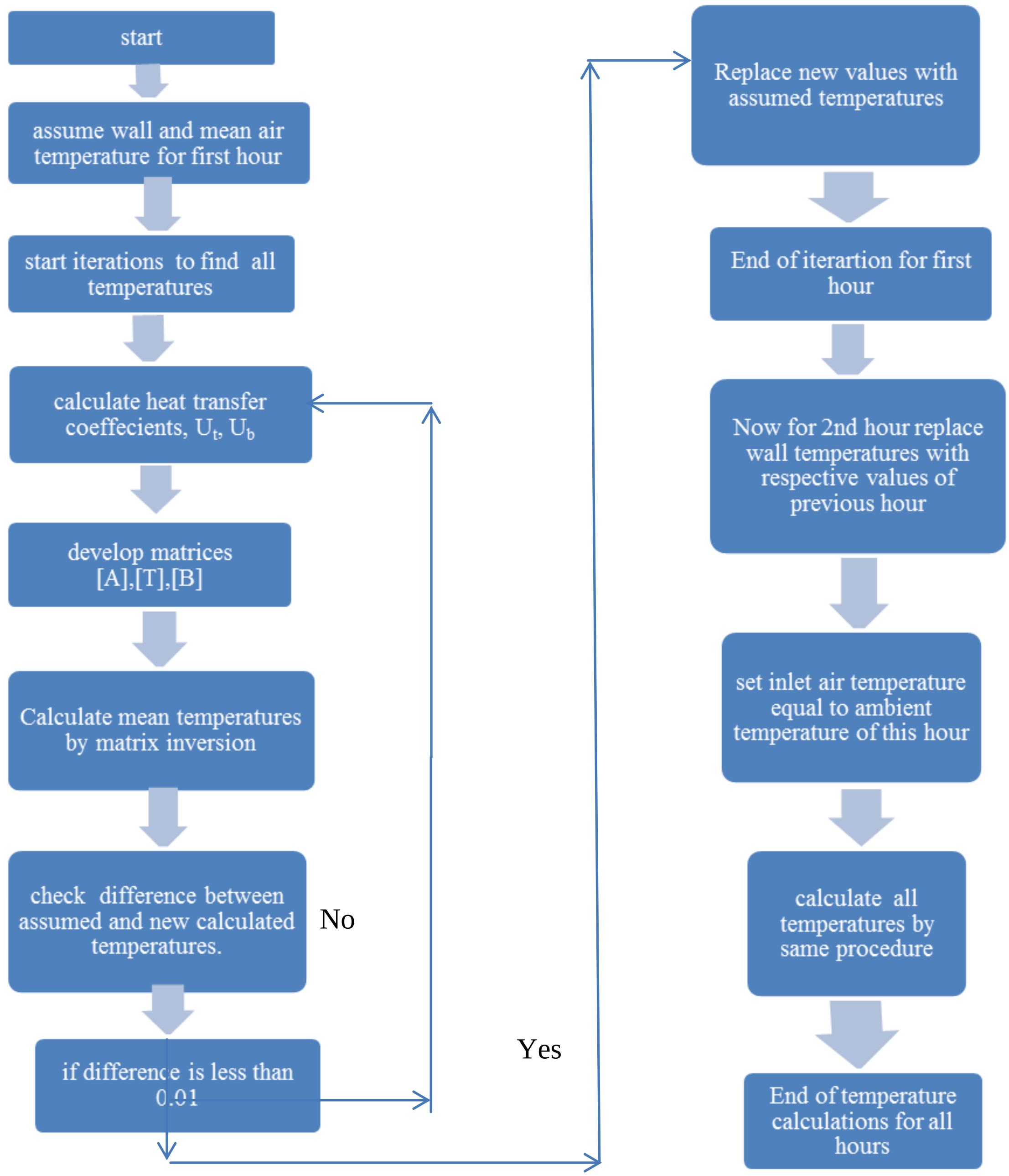


Figure 4.2: Simulation Algorithms for Thermal Analysis of Flat Plate Collector

4.2.4 Dryer Chamber

Computational fluid dynamics (CFD) analysis has been used to simulate the air velocity and temperature distribution inside the drying chamber. CFD results are presented in form of temperature contours to visualize the flow and thermal distribution along the height of chamber. CFD results are used to improve the design of dryer chamber. Dryer chamber consists of three perforated trays to place the products, bottom inlet for hot air and top exhaust fan.

Computational Implementations

A 2-D model of solar dryer geometry was created using GAMBIT version 2.3.16. The domain (chamber) was discretized into a finite number of cells by using structured grid of quadrilateral mesh elements (Fig.4.3). The governing equations for CFD are based on conservation of mass, momentum, and energy. FLUENT uses a finite volume method (FVM) to solve these equations. FVM is based on discretization of entire domain into small cells or control volume, and governing equations are solved over these cells and then extended over the entire domain [7]. Following assumptions have been made for the CFD analysis of drying chamber:

- Air flow inside the chamber is two-dimensional, in x and y direction.
- Flow is steady and compressible.
- Since the working fluid is air, so body forces can be neglected.

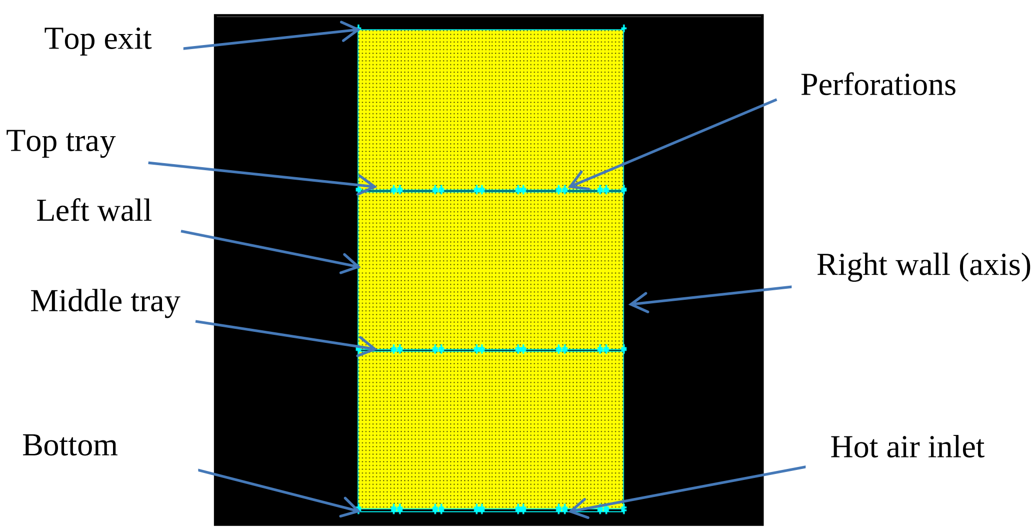


Figure 4.3: Gambit Model of Dryer Chamber

Simulation procedure

The dryer chamber has been modeled using turbulence model based on Reynolds-Averaged Navier Stokes (RANS) equations. In CFD simulation, the equations for flow, energy and turbulence equations were solved by using following solution and discretization schemes: Semi Empirical Pressure (SIMPLE), Standard and First Order Upwind scheme for Momentum and Turbulence Kinetic Energy. Convergence was checked by checking the computed scaled residuals: calculations were continued until the values of residuals were reducing by five or six orders of magnitude.

The boundary conditions of dryer model were divided into two sets: loaded and unloaded condition. Viscous- Laminar model with viscous heating was used in both conditions. Bottom inlet was taken as mass-flow inlet for hot air with flow rate of 0.01kg/s and temperature equal to that of inlet air. While top was taken as exhaust fan.

Right wall was taken as axis, so to model the same conditions on both sides of the wall. In loaded condition, all three trays were modeled using Temperature model with heat generation rate equal to the heat absorption rate of product volume placed on each tray. In this way each tray was acting as heat sink. While in unloaded condition heat generation rate on each tray was taken as zero. Unloaded condition was modeled to optimize the design of chamber and product placement inside the chamber.

4.2.5 Heat Exchanger

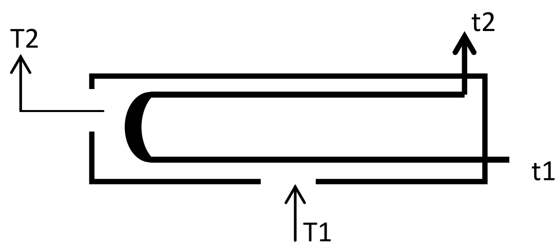
Heat exchanger serves the purpose of transferring heat from one fluid to another. All types of heat exchangers have a conducting element – in the form of tube or plate – that separate the two fluids and also provides the heat transfer surface.

Heat exchanger for hybrid solar dryer has been designed to prevent the smoke contamination in drying products due to biomass combustion. Shell and tube heat exchanger has been designed. Fresh air (cold stream) is sucked through a fan into the copper U-tube, while hot gases from burner (hot stream) enter the shell. Mathematical modelling and designing of heat exchanger has been done by LMTD (Log mean temperature difference) method [8][9].

Mathematical Modeling

Temperature of hot stream at inlet: T_1; Temperature of hot stream at outlet: T_2

Temperature of cold stream at inlet: t_1; Temperature of cold stream at outlet: t_2



The heat transfer rate from hotter to the colder fluid or heat duty (Q) is calculated as:

$$Q= \dot{m}_c C_{pc}(t_2-t_1)= \dot{m}_h C_{ph}(T_2-T_1) \quad (4.15)$$

Where subscripts c and h refer to cold and hot streams, respectively. Log mean temperature difference is:

$$LMTD= [(T_1-t_1)(T_2-t_2)] /\ln [(T_1-t_1)/ T_2-t_2)] \quad (4.16)$$

For 1 shell- 2 tube pass exchanger configuration, temperature correction factor (F_t) is calculated as:

$$F_t= \sqrt{(R^2+1)}\ \ln\left[\frac{1-S}{1-RS}\right] / (R-1) \ln [[2-S (R+1- \sqrt{(R^2+1)}\,] \ / [2-S (R+1+\sqrt{(R^2+1)}\,]]$$

Where $R= (T_1 - T_2)/(t_2 - t_1)$ and $S= (t_2 - t_1)/ (T_1 – t1)$. (4.17)

Mean temperature difference (DT_m) based on F_t is obtained as:

$$DT_m= Ft \times LMTD. \quad (4.18)$$

For shell and tube heat exchangers when both fluids are gases, overall heat transfer coefficient (U) is assumed in the range of 10-50 $W/m^2\text{-}^oC$. On the basis of this heat transfer area (A) is calculated as:

$$A= [Q/(U.\ DT_m)] \quad (4.19)$$

Based on assumed outer diameter of tube (d_o) and tube length (L), number of tubes (N_t) is:

$$N_t= A/(3.14 \times d_o \times L) \quad (4.20)$$

Tube Pitch (P_t) is the smallest distance from center of one tube to center of second tube:

$$P_t = 1.25\ d_o \quad (4.21)$$

Bundle diameter: $D_b = d_o\ (N_t/K_1)^{\wedge}1/n_1$ (4.22)

Where K_1 and n_1 are obtained from graph based on the tube arrangement (Triangular or square pitch).

Based on the number of tubes and bundle diameter obtained from above equations, the shell is designed accordingly in order to enclose the tubes. The shell is insulated from all sides to minimize the heat losses.

4.2.6 Temperature Sensor

The temperature circuit has been designed to indicate the temperature limit inside the drying chamber. Integrated circuit (IC) of temperature sensor consists of following main components:

- Temperature sensor- LM35
- Microcontroller - PIC18F452.
- Capacitors (33 PF each)
- Resistors (100 Ω each)
- LED lights (Red & Green)

Other components include push switches, three pin cream shell, etc. The LM35 is a precision integrated-circuit temperature sensor, which produces output voltage linearly proportional to the temperature (^oC), and does not require any external calibration. The temperature range of LM35 is -55 to 150^oC, and scale factor is +10 mV/^oC [10].

It senses the temperature inside drying temperature; microcontroller has been programmed that when dryer temperature exceeds 60^oC, red LED will indicate. Microcontroller programing has been done using 'Micro C', after that Schematic capture and PCB layout was designed using 'Proteus 8' software. The schematic capture of temperature sensor circuit is shown in Fig 4.4

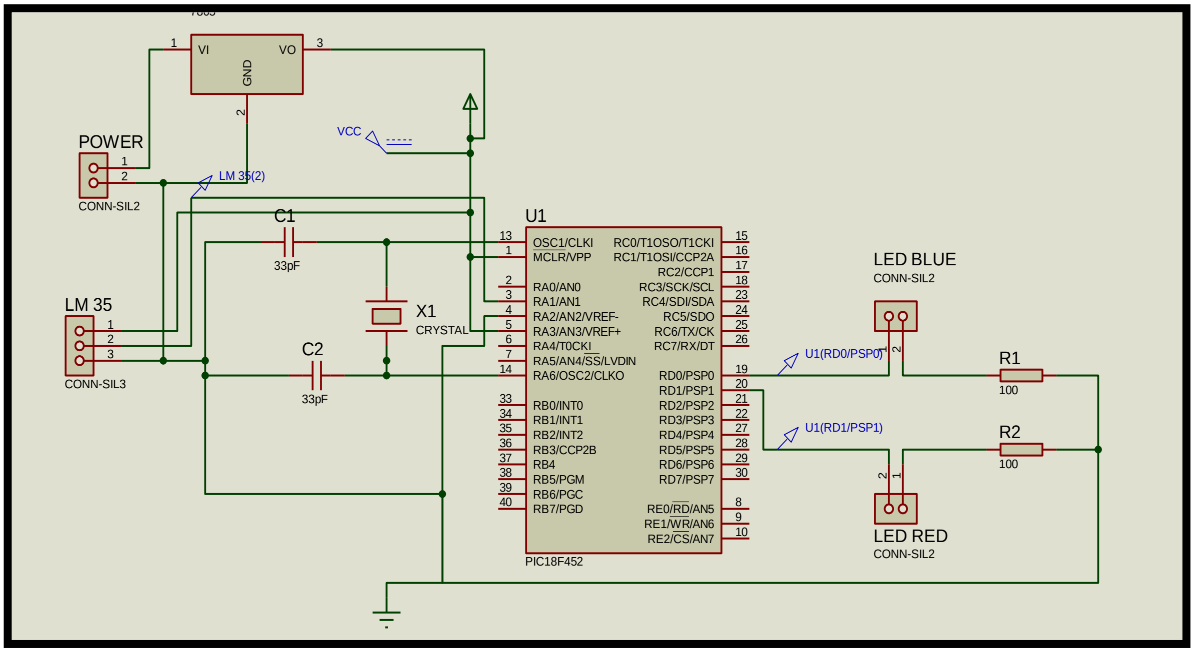


Figure 4.4: Schematic Capture of Temperature Sensor Circuit

4.3 Fabrication of Lab Scale Hybrid Solar Dryer

Based on mathematical modeling and simulation results, lab scale prototype of solar dryer has been fabricated at Manufacturing Resource Center (MRC)-NUST, using locally available materials and technology. Lab scale solar dryer consists of following main components:

4.3.1 Flat Plate Solar Air Collector

Solar air collector consists of following main components:

- Glazing (Top glass cover)
- Absorber Plate
- Insulation

Single cover of low iron content-tempered glass was used as glazing material. A corrugated aluminum plate was used as absorber, and painted black to enhance its absorptivity. Aluminum is highly conductive material (thermal conductivity:205W/m-K) and economical as well. To minimize the heat losses, bottom and edges of the collector were insulated with glass wool insulation. This is single air channel flat plate collector: the gap (25mm approx.) between absorber and glass cover serves as the air channel. The whole collector assembly was enclosed in a rectangular box of GI sheet. A rectangular hole for fresh air inlet has been drilled in front side of the collector box. And outlet pipe for hot air has been fixed at other end of the collector. An air tight nozzle was fixed at the end of the collector box to add fresh air in case of high temperature (above $60^{o}C$).

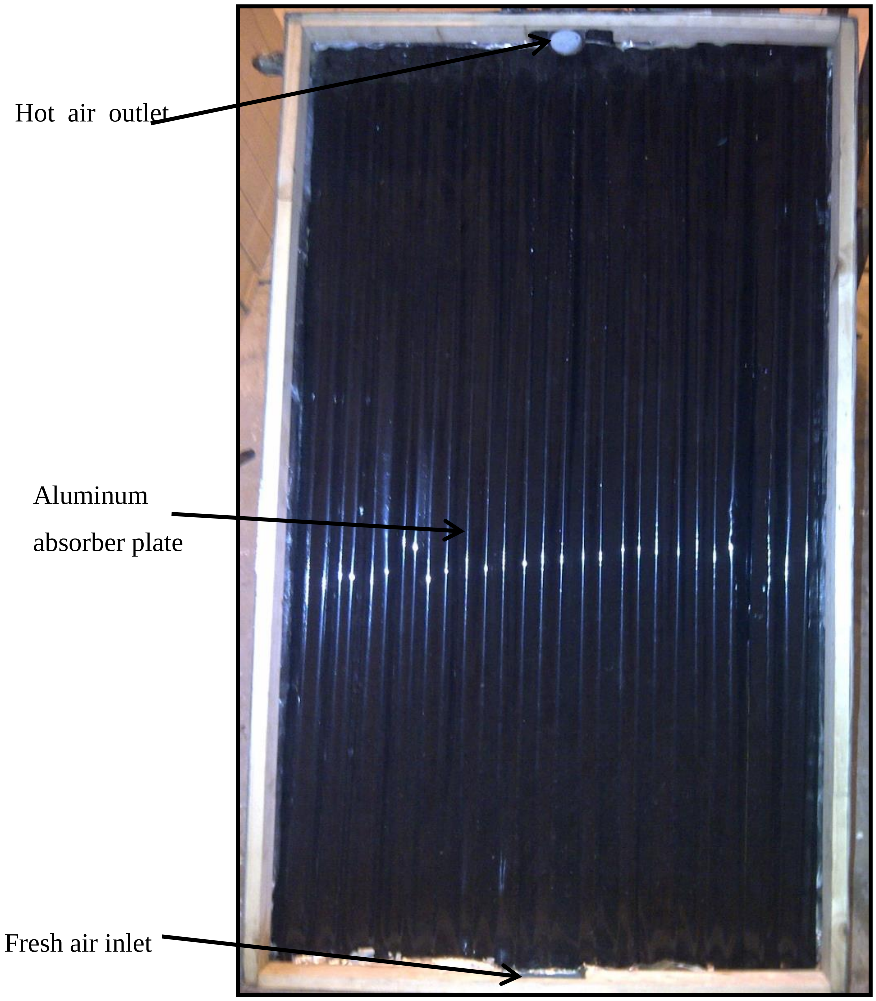


Figure 4.5 Flat Plate Solar Air Collector- Physical Model

Figure 4.6 Flat Plate Solar Air Collector- Physical Model

Dimensions of flat plate solar air collector and materials of fabrication are given in table below:

Table 4.2: Dimensions and Materials of Flat Plate Solar Collector

Component	**Dimensions**	**Fabrication Material**
Top cover	L*W: 1*0.5 m. Thickness: 4mm	Tempered glass
Absorber plate	L*W: 1*0.5 m. Thickness: 1mm	Aluminum
Insulation	L*W: 1*0.5 m. Thickness: 50mm	Glass wool insulation
Collector box	L*W= 1.1*0.6m H= 0.1m	18 Gauge GI sheet

4.3.2 Dryer Chamber

Dryer chamber consists of three perforated sliding trays to place the products, and one front door. All trays are oriented vertically with equal gap between each other (5 inch approx.). It has two bottom inlets for hot air: one from solar collector and another from heat exchanger. And one top vent for exhaust fan. Exhaust fan force the hot air at required flow rate from solar collector or biomass burner into the drying chamber. Door and all sides of chamber are insulated with glass wool insulation to minimize the heat losses. Dryer chamber is fixed on an iron stand.

Figure 4.7: Dryer Chamber- Fabricated Model

Materials used for fabrication are given in following table along with detailed dimensions of chamber:

Table 4.3: Dimension and Materials Of Dryer Chamber

Component	**Dimensions (inch)**	**Fabrication Material**
Perforated trays	12*12*1	Stainless steel (SS)
Perforation size	0.15 (4mm)	------
Front door	20*10	18 Gauge GI sheet
Dryer chamber	16*16*23	18 Gauge GI sheet
Insulation	0.9 (25mm)	Glass wool

4.3.3 Biomass Burner

A piece of pipe from the 20 liter photobioreactor was taken and placed in a fish tank with 30 liter algae already growing in it. The pipe was left undisturbed in the tank for 20 days after which the Biofilm was fully grown, the pipe was then converted into fragments and then different algal Biofilm removal method was applied.

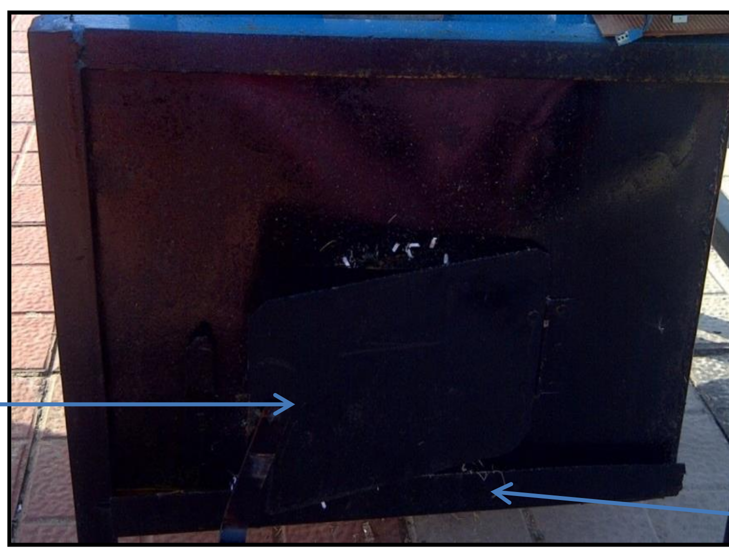


Figure 4.8 Biomass Burner - Fabricated Model

Table 4.4 Dimensions and Material Of Biomass Burner

Component	Dimensions (inch)	Fabrication Material
Burner box	15*15*13	18 Gauge GI sheet
Ash tray	15*15	18 Gauge GI sheet

4.3.4 Heat Exchanger

Heat exchanger for hybrid solar dryer has been designed to prevent the smoke contamination in drying products due to biomass combustion. Shell and tube heat exchanger has been designed because it provides higher heat transfer area, more economical for low temperature rise and it is easy to manufacture as compared other types of heat exchangers like plate and frame, and coil type.

Fresh air (cold stream) is sucked through a fan into the copper U-tube, while hot gases from burner (hot stream) enter the shell. Hot gases circulating in shell heat the copper tube, which in turn transfers heat to the cold air inside. Then air from copper tube enters the dryer chamber above. And burner flue gases exit through a chimney. Through this arrangement of fluids we were able to get more heat transfer area and as a result more uniform temperature rise of fresh air. The copper tube is removable to facilitate the cleaning process afterwards. Shell is insulated from all sides with glass wool insulation to minimize the heat losses. Heat exchanger specifications have been selected on the basis of mathematical modelling results.

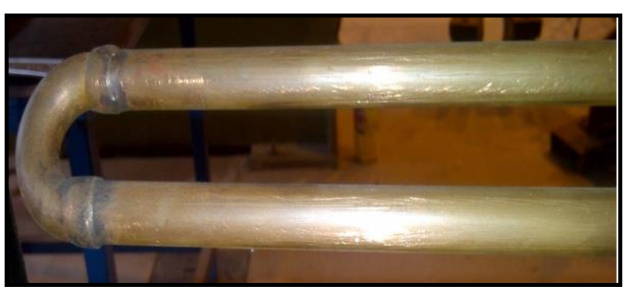


Figure 4.9 Copper U-Tube

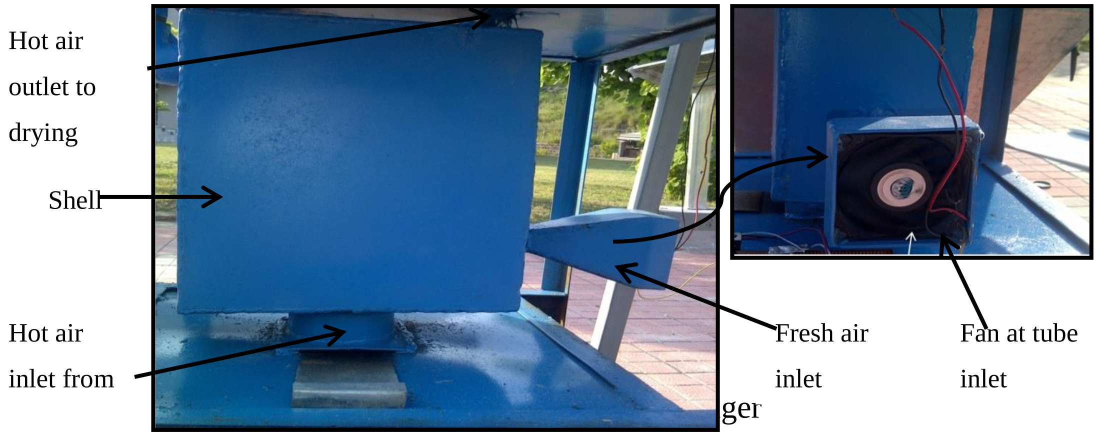


Table 4.5 Dimensions and Material Of Heat Exchanger

Component	Dimensions (inch)	Fabrication Material
Copper U-tube. No of bends= 1	L= 20, Diameter= 1	Copper
Shell	L*W*H = 12*6*11	18 Gauge GI sheet
Hot air inlet pipe	Diameter : 3	GI
Fan	Diameter: 3	Plastic

Fan specifications are: Maximum air flow: 31.6 CFM. Speed: 2500RPM. Rated input: 1.56 W. Rated voltage: 12V. Maximum air pressure: 2.83mmH_2O.

4.3.5 Temperature Sensor Circuit

The temperature circuit has been designed to indicate the temperature limit inside the drying chamber. So we can maintain the optimum drying temperature inside the chamber. The microcontroller has been programed to give indication when temperature of the drying chamber exceeds 60^oC. Temperature sensor LM35 is fixed inside the drying chamber. Components of temperature sensor IC has already been mentioned along with schematic capture. The temperature sensor-LM35 and IC of sensor is shown in Figure 4.11.

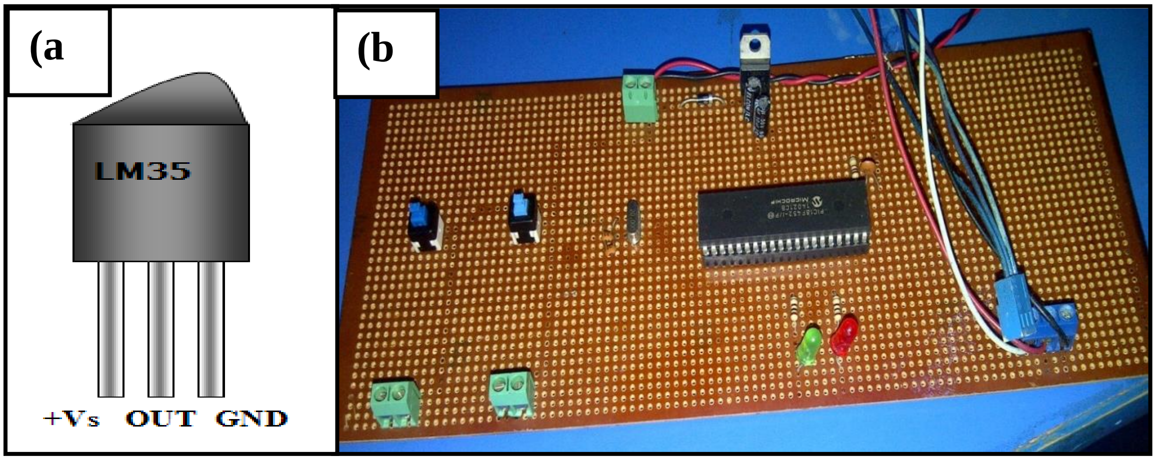


Figure 4.12 (a Temperature Sensor. (b Temperature Sensor Circuit

4.4 Lab Scale Prototype of Hybrid Solar Dryer

Complete setup of hybrid solar dryer:

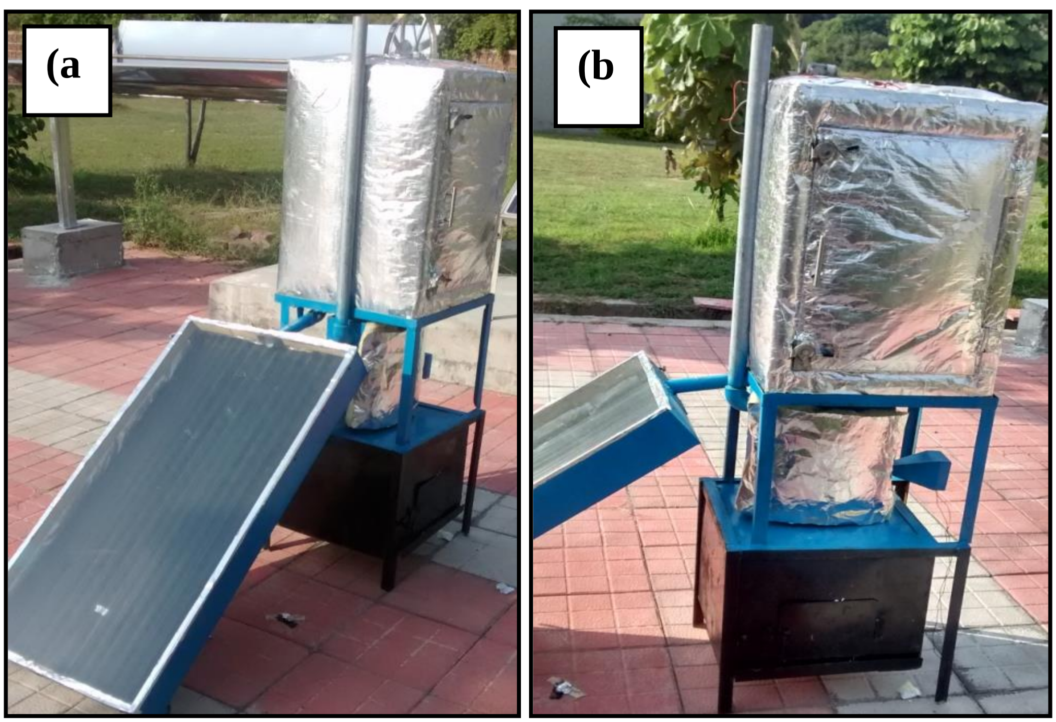


Figure 4.13 Hybrid Solar Dryer- Lab Scale Prototype

Summary

This chapter presents the methodology and procedures to develop an indirect-mode forced convection hybrid solar dryer model. Mathematical modeling and simulation of flat plate solar air collector has been done using MATLAB and algorithm to predict thermal performance of solar collector has also been presented. CFD analysis of dryer chamber using FLUENT estimates the thermal distribution of hot air along the chamber height. And also optimizes the chamber design. Detailed mathematical modelling and design procedure of Shell and tube heat exchanger by LMTD method has been presented in this chapter. To control temperature inside the dryer chamber, integrated circuit of temperature sensor has been programed in PROC software. Based on mathematical modeling and simulation results, lab scale prototype of solar dryer has been fabricated at Manufacturing Resource Center (MRC) at NUST, using locally available materials and technology.

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CHAPTER 5

EXPERIMENTAL ANALYSIS

This chapter presents the experimental analysis that was done to assess the thermal performance of designed hybrid solar dryer. All the experimental work was carried out at Center for Energy Systems (CES)-NUST, Islamabad. The monitoring parameters, instruments and operational conditions of solar dryer have been mentioned.

5.1 Monitoring Parameter

5.1.1 Solar Radiation Intensity

The hourly solar radiation intensity at the surface of solar collector was measured, to investigate the variation in performance of solar collector and dryer. Light meter was placed on the solar collector and radiations were recorded after every 60 minutes from 8 a.m. to 5 p.m.

Figure 5.1: Digital Light Meter

5.1.2 Temperature

Top cover temperature, absorber and hot air temperature at the collector outlet was measured using digital multimeter (Unit-T, UT33C) and thermometers (Digi-thermo, WT-2). Hot air temperature inside the drying chamber was measured at the bottom, middle and top tray. All the temperature readings were recorded after every 30 minutes in each hour, and average value was calculated for each hour from 8 a.m. to 5 p.m. Hot air temperature inside the drying chamber was recorded in loaded and unloaded condition as well.

Figure 5.1: Temperature Sensor

5.1.3 Product Mass or Moisture Content

During the drying process, product mass was measured using an electronic mass balance (Model EK-300i) of readability 0.001g. Product sample from each tray was taken from the dryer and weighed at one hour interval during the drying process, until constant weights were observed. At the end of drying process, product sample was dried in a hot air oven at 101^{o}C for 24 hour to determine the final weight of the product when it was completely dried. During the drying process, the drying products were stirred manually at regular intervals to ensure uniform drying[1] [2].

:Figure 5.2: Digital Mass Balance

5.1.4 Solar Collector Efficiency (Ƞsc)

Average solar collector efficiency was calculated as:

$$Ƞsc = Q/IA \tag{5.1}$$

Where I is solar radiation intensity (w/m^2) that was measured using light meter. And A is collector area. Q is thermal energy transferred to flowing air which is calculated as:

$$Q = \dot{m} \times C_p(T_o\text{-}T_i) \tag{5.2}$$

Where ṁ is mass flow rate in the drying chamber, C_p is specific heat capacity of air (1.005 KJ/Kg-Kat 300K). And T_o, T_i is average outlet and inlet air temperature, respectively [3].

5.2 Experimental Setup

The drying experiments were conducted during the month of September-2014, to assess the thermal performance of designed hybrid solar dryer. For drying tests, mint leaves with initial moisture content of 78% were dried. Mint is a medicinal plant and also used in spices. Before drying, stems and spoiled leaves were removed. Two tests were conducted to determine the temperature variation inside the dryer chamber under unloaded condition. Collector cover and absorber temperature and outlet air temperature were also recorded during each experiment. Two drying tests were conducted for drying mint leaves: one test under solar drying and one test under biomass combustion in cloudy weather.

The dryer was designed to utilize solar radiation as main energy source for drying operation. The biomass burner was designed as a supplement heat source; to be used only under cloudy or rainy condition or during night time when continuous drying process is required. Under solar drying operation, hot air from solar collector enters the drying chamber form bottom and rises up under forced convection due to fan. The hot air rises up through perforated trays, dehydrates the drying products and get exhausted through top vent.

During low insulation period or night time, the biomass burner serves as the heat source. Hot air (smoke) from burner enters the heat exchanger shell, where fresh air inside the copper tube gets heat up. This hot air then enters the drying chamber from bottom, absorbs moisture from products and escapes through top vent as before. Smoke exits through chimney. During solar or hybrid mode, it is critical to maintain the optimum drying temperature inside the chamber.

Temperature control

The dryer chamber can be controlled by regulating the air flow rate or temperature of incoming air. In designed lab scale dryer, it was difficult to regulate the air flow rate so we had to control the temperature of incoming air from solar collector or heat exchanger.

In solar drying mode: if temperature inside the chamber exceeds 60^oC (this will be indicated by LED), air nozzle on the side of collector is opened to mix fresh air with hot air at collector outlet before it enters the chamber. So the temperature inside the chamber drops to desired limit.

In hybrid mode: if temperature inside the chamber exceeds 60^oC (this will be indicated by LED), a slit on heat exchanger inlet can be closed so the hot air from burner would not enter the exchanger and then chamber. To further reduce the dryer temperature, air nozzle of collector can also be opened to suck fresh air inside the chamber.

5.3 Drying Analysis

Following equations and principles has been applied for the drying analysis of the products:

$$\text{M.C on wet basis } (M_{ow}) = W_o\text{-}W_d/W_o \quad (5.3)$$

Where W_o is the initial weight of product (kg), and W_d is the weight of the dried product.

$$\text{M.C on dry basis } (M_{od}) = W_o\text{-}W_d/W_d \quad (5.4)$$

The instantaneous moisture content (M_t) at any given time t on dry basis:

$$M_t= [(M_{od}+1)*W_t/W_o]-1 \quad (5.5)$$

Where W_t is the weight of product at any time (kg), and W_o is the initial weight of product (kg).

Moisture ratio (MR): $MR = M_t/M_o$ (5.6)

Where M_o is initial moisture content of the product (dimensionless).

In literature thin layer drying behavior of mint is described by Midilli and Kucuk model.

Midilli and Kucuk model:

$$MR = 0.9891\exp(-0.0568t^{3.0459)} + 0.029t. \quad (5.7)$$

The experimental results of mint drying were compared with modelling results obtained from above model[1][4][5].

Summary

This chapter presents the experimental analysis that was done to assess the thermal performance of designed hybrid solar dryer. Solar radiation intensity, temperature of drying air and collector surface, product mass were continuously measured during each experiment by using light meter, digital temperature sensors, and electronic mass balance, respectively. Experimental setup and conditions has also been described in detail. After recording experimental values, drying analysis has been done using mathematical equations and models.

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CHAPTER 6

RESULTS AND DISCUSSSION

This chapter presents the results obtained from numerical simulation and through experimental analysis of designed solar dryer. Comparative study proves good agreement between predicted and experimental results. Commercial scale model of hybrid solar dryer for MAPs drying in northern areas of Pakistan has also been presented in this section.

6.1 Solar Collector Performance

All the experiments were carried out during September-2014, at CES-NUST. The solar dryer was placed outdoor and readings were recorded from 8 a.m. to 5 p.m. with same procedure as described in chapter 5. Temperature variation in collector's cover, absorber and outlet air was recorded after every 30 minutes, and average value was calculated for each hour. Figure 6.1 presents the solar radiation intensity during the experiment. Average solar intensity was around 667 W/m^2 and peak radiation was recorded at 12 p.m.

Figure 6.2 presents the simulation result for collector's cover temperature, absorber and outlet air temperature, calculated using mathematical model and simulation algorithm described in section 3.2.1.2. Figure 6.3 presents the temperature histories recorded for flat plate solar collector on 9th September. It is evident from graph that absorber temperature is highest as compared to cover and outlet air. This is because of high absorptivity of absorber plate, while cover temperature is the lowest due to losses to ambient air. The outlet air temperature is always 5-10^{o}C lower than absorber temperature, this is because of poor heat transfer properties of air as compared to water.

Simulated results show the higher absorber temperature as compared to experimental findings. Because in numerical modeling standard values for selective absorber coatings have been used, while common black paint have quite lower absorptivity. Cover and outlet air temperature are close to experimental values. Overall comparison proves good agreement between simulated and experimental results of flat plate solar air collector.

Table 6.1 Weather Detail of Experimental Date

Day	**Maximum ambient temperature ^oC**	**Minimum ambient temperature ^oC**	**Weather**
9thSep,2014	34	27	Sunny

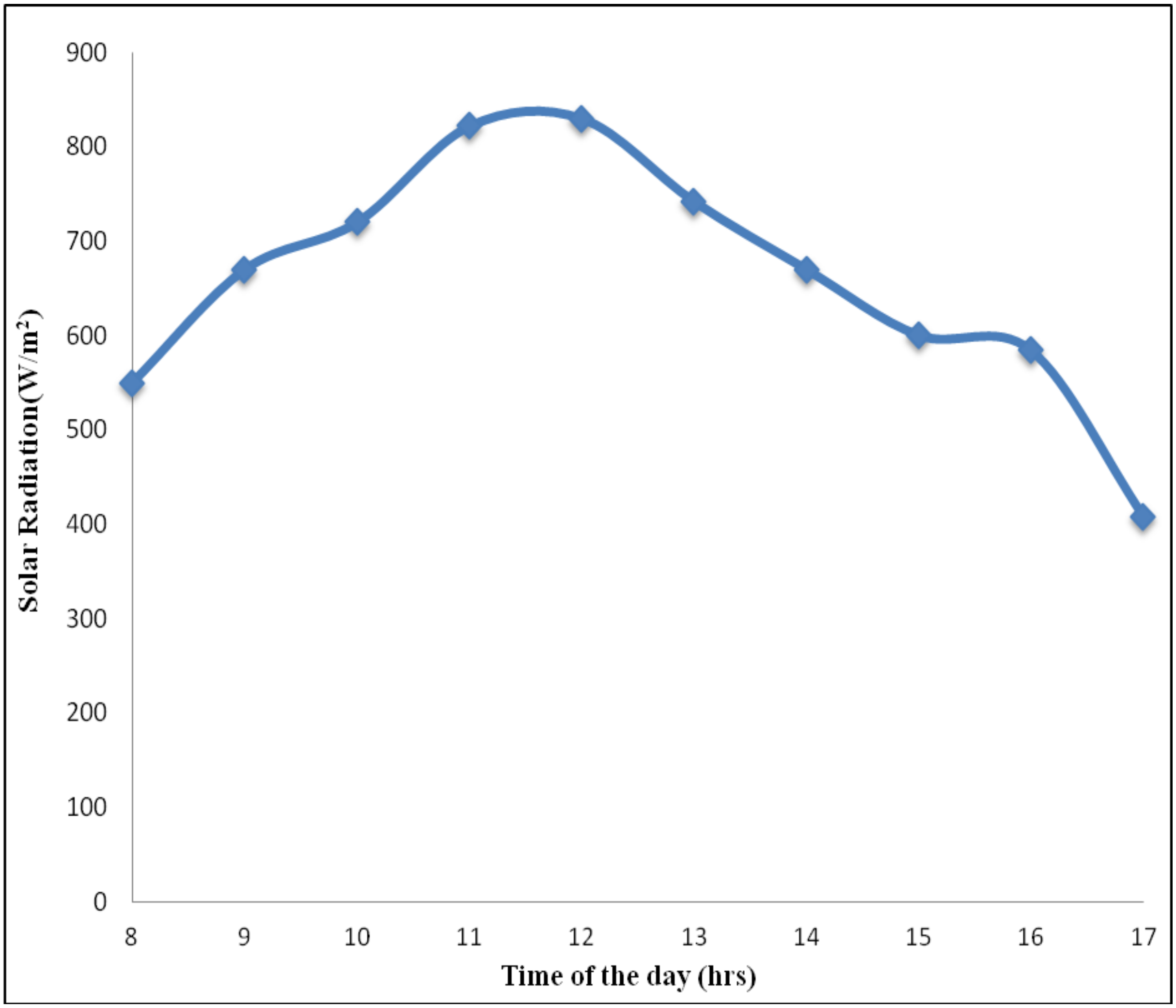

Figure 6.1 History Of Recorded Solar Radiation On 9th September

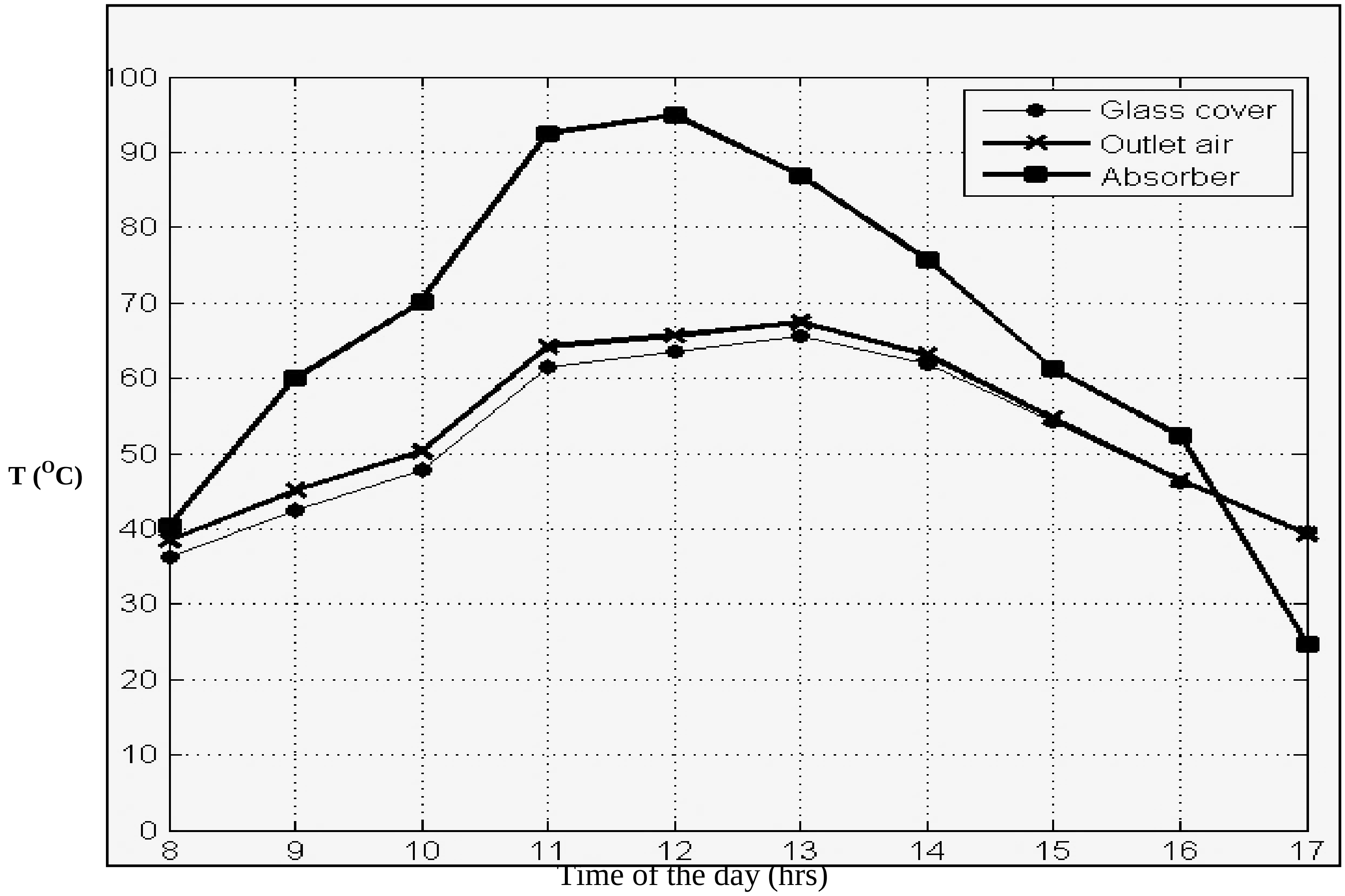

Figure 6.2 Simulation Results For Flat Plate Solar Air Collector

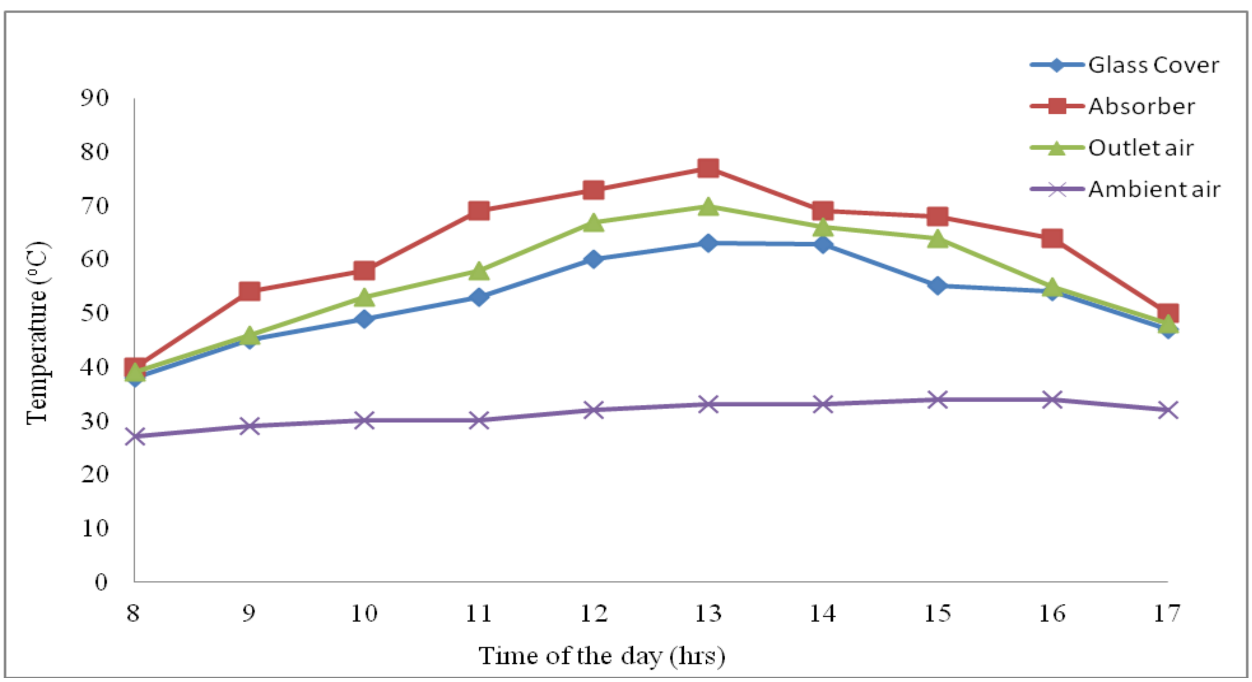

Figure 6.3 Recorded Temperature Histories for Flat Plate Solar Air Collector on 9th September

6.2 Dryer Chamber Performance

Figure 6.4 presents the simulation results of dryer chamber temperature in unloaded condition, numerical model and boundary conditions have been described in chapter 4. Simulation results of unloaded condition helped in designing of chamber and product placement afterwards in experimental work. Fig 6.5 presents the simulation results of dryer chamber in loaded condition (boundary conditions has been mentioned in chapter 4). Modelling results in both cases present almost similar temperature variations along the chamber height as in experimental results.

In experimental work, bottom, middle and top tray temperatures were recorded with the help of temperature sensors (instruments and method mentioned in chapter 5). Trays' temperatures were measured in order to assess thermal variation along the height of chamber, in loaded and unloaded conditions as well.

In both conditions, top tray temperature is the highest and then temperature drops as hot air moves up. In unloaded condition: middle and top tray temperatures are almost same (1 or 2 ^{o}C difference), while in loaded condition: middle and top tray temperature reduces further and difference between these also increases. This is because as the hot air moves up it absorbs moisture from products placed in tray, so top tray temperature would be much reduced now (5-10^{o}C difference). In loaded condition outlet air temperature reduces further than that in unloaded condition (figure 6.6- 6.7).

Table 6.2 Weather Detail Of Experimental Dates

Day	Maximum ambient temperature ^{o}C	Minimum ambient temperature ^{o}C	weather
10th Sep	33	27	Sunny
11th Sep	31	24	Sunny

Temperature (K)

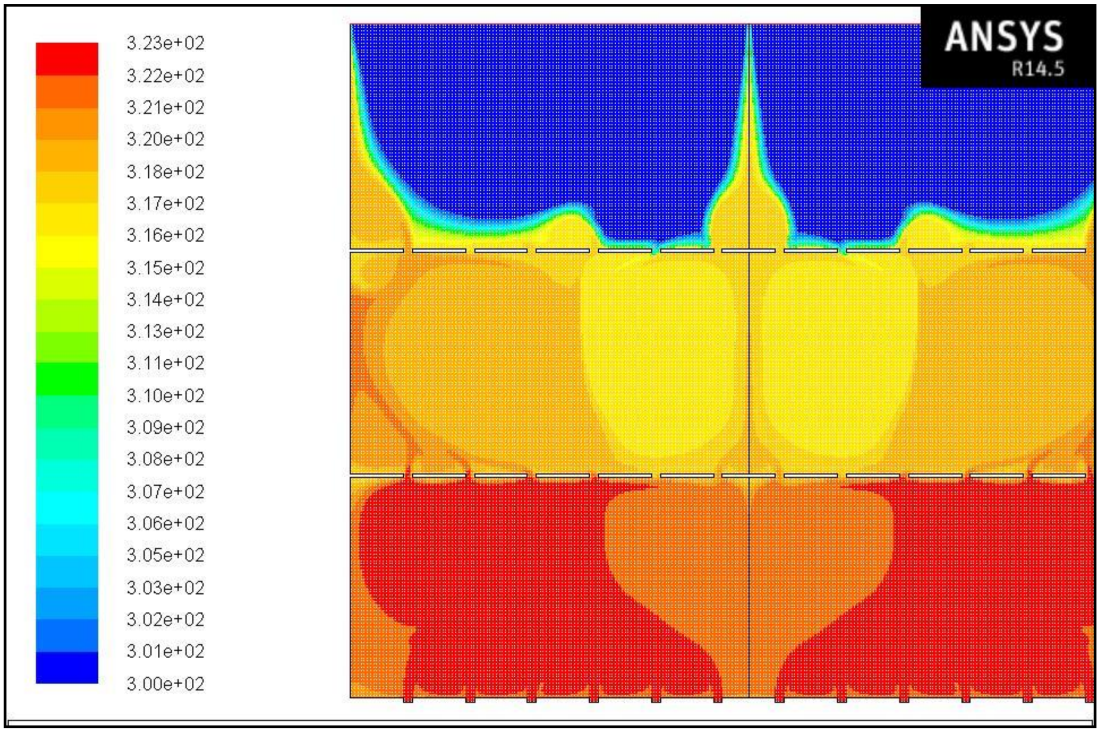

Figure 6.4 Simulation Results- Dryer Chamber Temperatures in Unloaded Condition

Temperature (K)

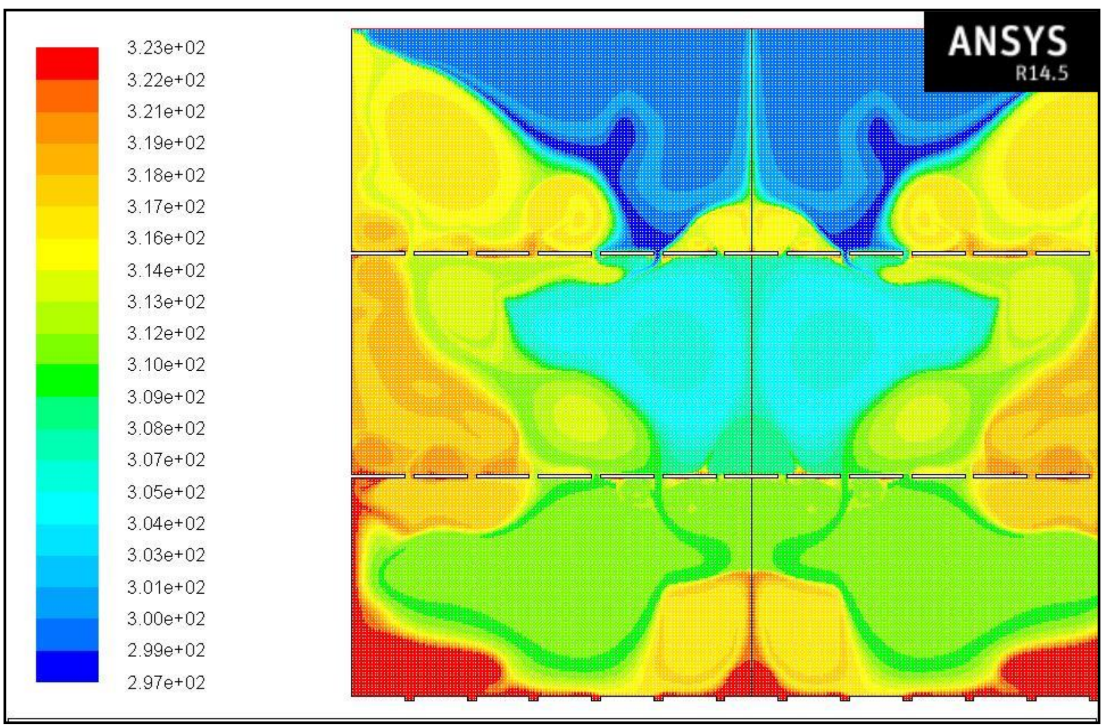

Figure 6.5 Simulation Results- Dryer Chamber Temperature in Loaded Condition

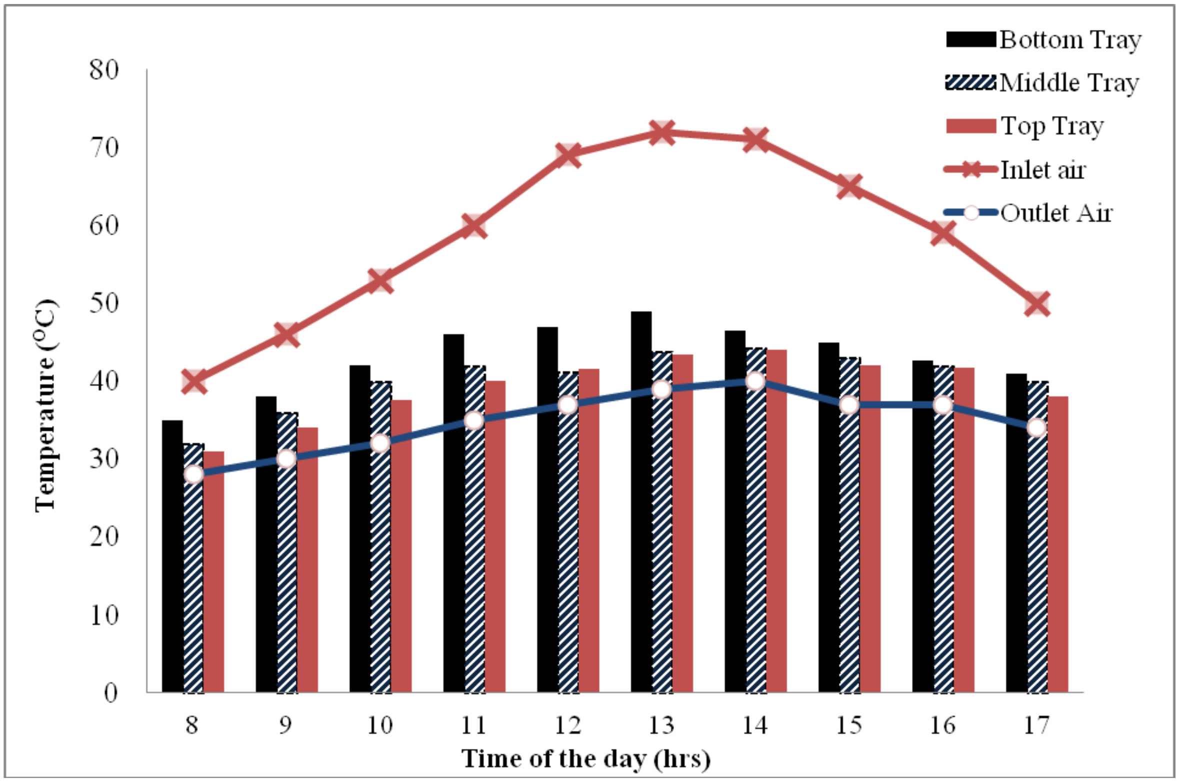

Figure 6.6 Recorded Temperature Histories Of Dryer Chamber- Unloaded Condition

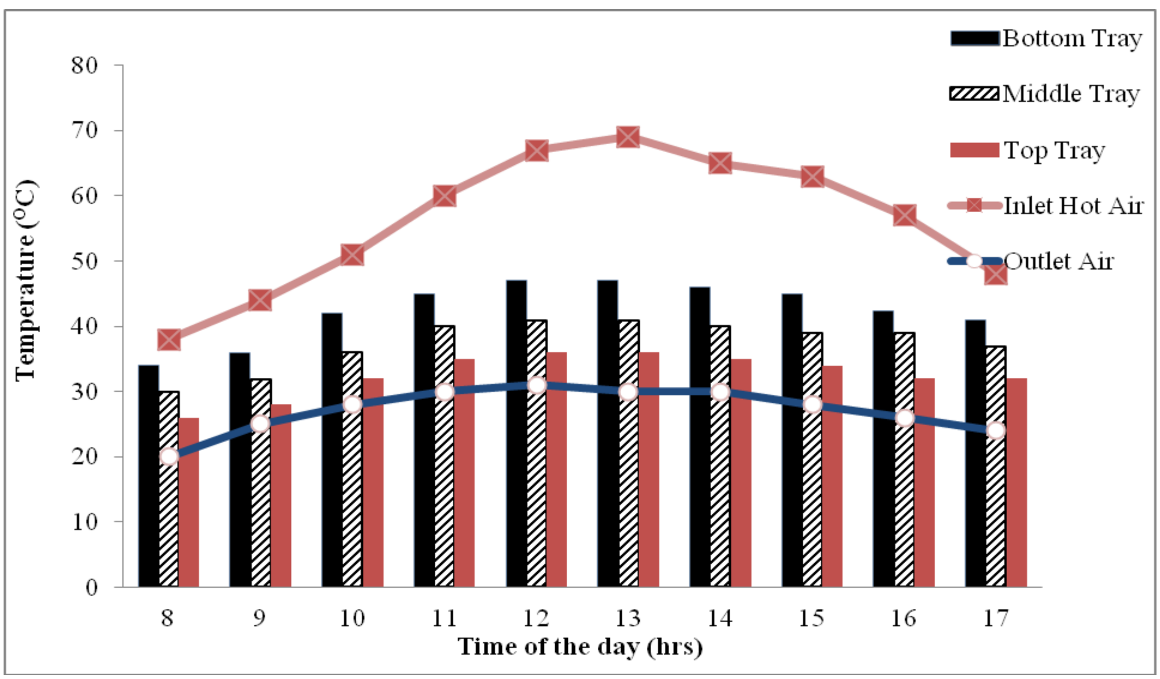

Figure 6.7 Recorded Temperature Histories Of Dryer Chamber- Loaded Condition

6.3 Drying Experiment

For drying tests, mint leaves with initial moisture content of 78% were dried (method has been described in chapter 5).Two drying tests were conducted for drying mint leaves: one test under solar drying and one test under biomass combustion in cloudy weather. Drying was continued until mint leaves attained final/equilibrium moisture content. Equations governing the drying experiment have been discussed in section 5.3.

Table 6.3 Weather Detail Of Experimental Dates

Day	Maximum ambient temperature ^{o}C	Minimum ambient temperature ^{o}C	Weather
12th Sep	30	26	Sunny
16th Sep	29	24	Mostly cloudy

Figure 6.8 shows the drying result of mint leaves under solar drying on 12th September. Figure 6.9 presents the experimental values of M.R computed form equation 5.6

Table 6.4 Experimental Conditions and Drying Results of Mint Leaves under Solar Drying

Parameter	**Operational condition**
Heat source	Flat plate solar air collector
Air mass flow rate (ṁ)	0.01kg/s
Average drying Temperature	50^{o}C
Initial Moisture content	78%.
Drying Result	
Final Moisture Content	12%
Total drying time	5 hours.(approx.)
Moisture removal efficiency	84%

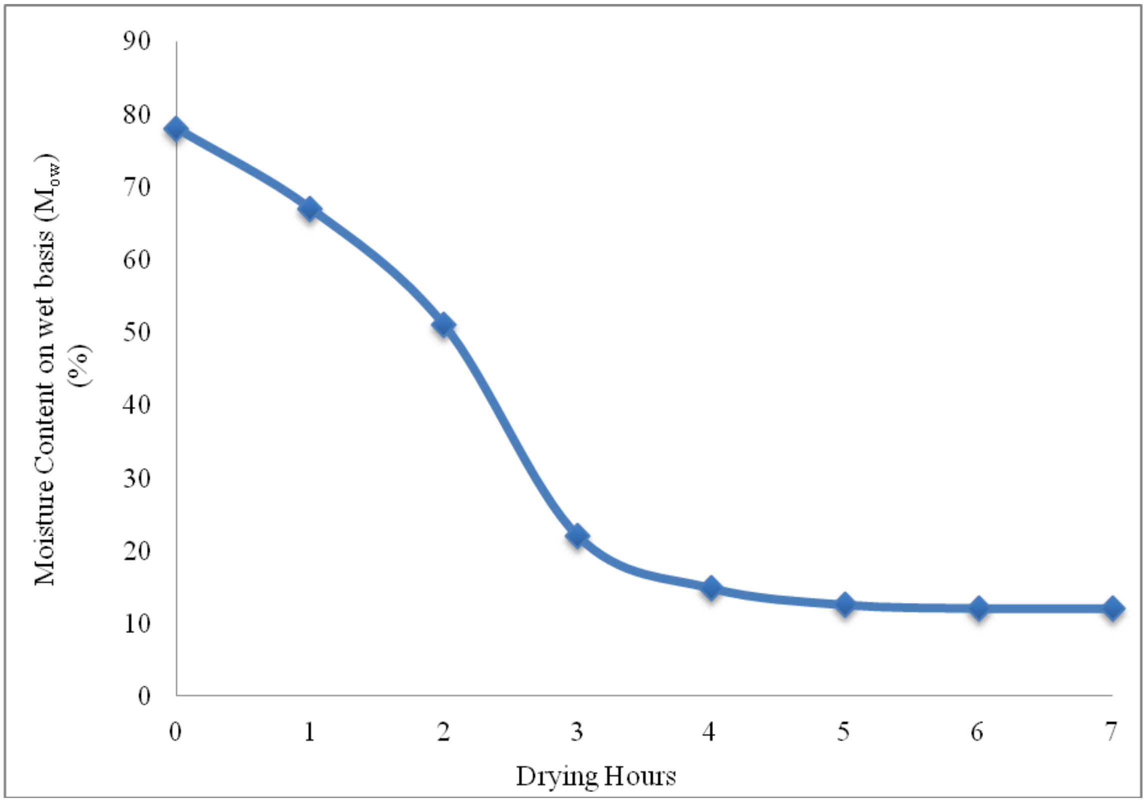

Figure 6.8 Mint Leaves Drying Result Under Solar Drying On 12th September.

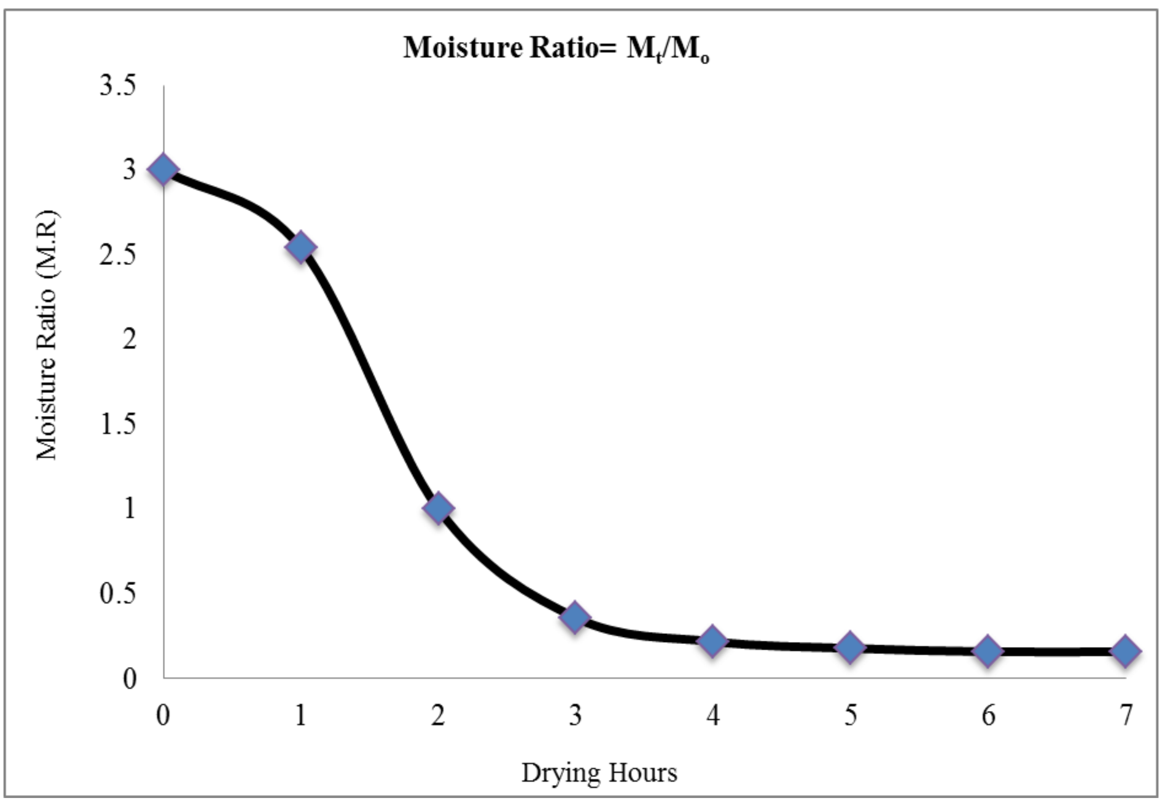

Figure 6.9 Moisture Ratios of Mint Leaves Drying

Midilli and Kucuk model was used to model mint leaves drying as explained in section 5.3. Figure 6.10 compares the experimental results of M.R with numerical prediction. Experimental values are quite close to predicted values over the drying period, except little variation at start of the experiment.

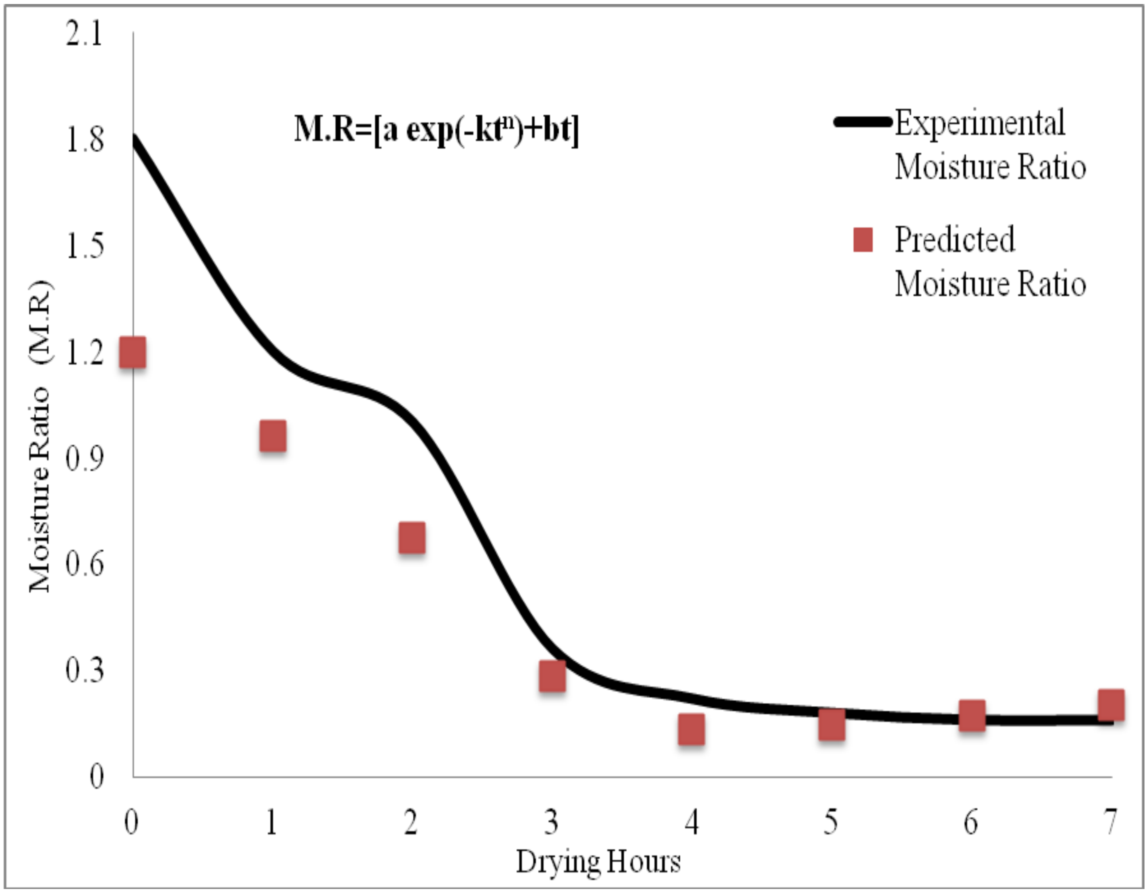

Figure 6.10 Moisture Ratios of Mint Leaves Drying

In second experiment mint leaves were dried using biomass heat source on 16th September. Hot air from biomass burner enters the heat exchanger where it transfers heat to the fresh air in copper tube. Then hot air from heat exchanger enters the drying chamber from bottom inlet. Operational conditions during experiment and drying results have been mentioned in following table

Table 6.5 Experimental Conditions and Drying Results of Mint Leaves Under biomass combustion

Parameter	Operational condition
Air mass flow rate (ṁ)	0.01kg/s
Average drying Temperature	55^{o}C
Initial Moisture content	78%.
Drying Result	
Final Moisture Content	12%
Total drying time	3 hours.(approx.)
Moisture removal efficiency	84%

Figure 6.11 presents the mint leaves drying result using biomass heat source. It is evident that mint leaves attained final or equilibrium moisture content (12%) more rapidly as compared to solar drying, because biomass combustion provides more consistent and rapid heating as compared to solar drying. That's why drying time now have been reduced to three hours.

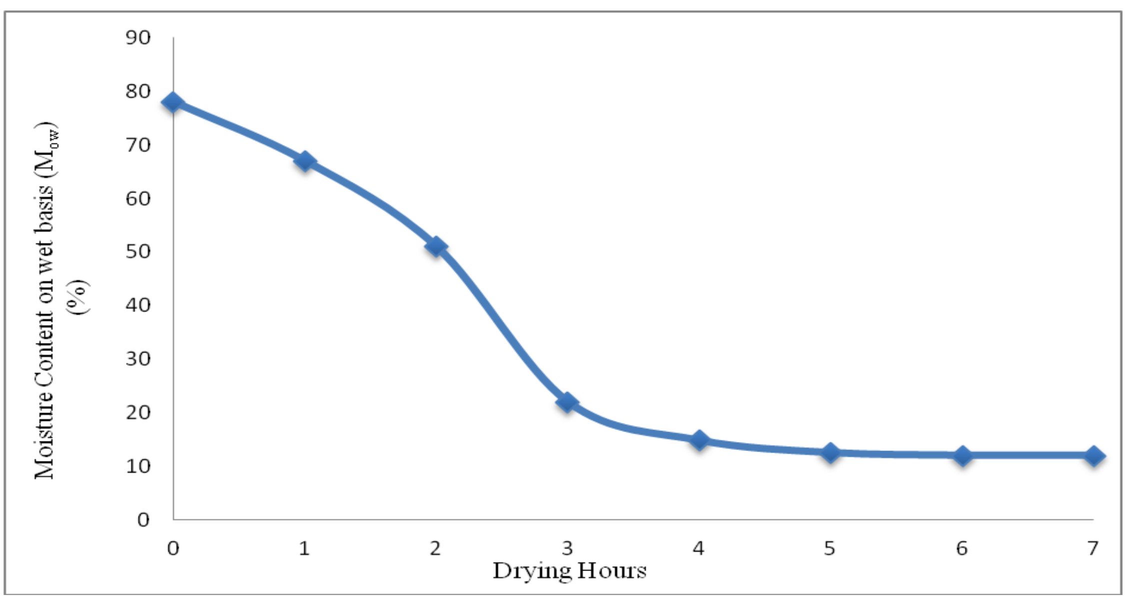

Figure 6.11 Mint Leaves Drying Result Under Biomass Combustion On 16th September

Figure 6.12 a) Fresh mint leaves. b) Dry mint leaves

6.4 Hybrid Solar Dryer-Commercial Scale Model

Based on results of lab scale prototype solar dryer, commercial scale model has been proposed after careful assessment of Maps' drying load, metrological data and field visits of target areas in Khyber Pakhtoon Khawa (KPK)-Pakistan.

6.4.1 Field Survey of Target Areas

To assess the MAPs potential in project impact areas and feasibility of solar drying, field visits were conducted in District SWAT, SHANGLA and Upper DIR in KPK, (from October 26-November 10, 2013). Target union Councils (UCs) in all three districts include: Districts Swat (UCs : Islampur, Chiil, Beshigram, Sakhra, Miandem and Dermai), District Shangla (UCs: lenolai and Yakhtangi) and Upper DIR (UCs: Barawal and Tarpatar). As a result of field assessments and meetings with selling agents, certain potential sites have been identified.

Figure 6.13 Site Visits of Target Areas In KPK

6.4.2 Study Of Meteorological Data Of Project Impact Areas

Meteorological data of the sites (District: SWAT, SHANGLA, UPPER DIR) has been checked from PMD which shows approx. 270-300 clear sunny days when the solar intensity is approx. 4-4.5KWh/m^2-day. With this available annual average solar intensity in the project areas, a community based solar dryer may be proposed. In the light of the available information from PMD and METEONORM data base, the above mentioned PSH i.e. Peak Sun Hours available on a yearly average base are enough to have appropriate energy from sun for solar drying operation.

Keeping in view the available PSH different simulations on T-SOL, POLYSUN reveals that the energy required in KWh/day or MJ for preheating the air for dehumidification is enough to have 500Kg of wet MAP's for drying. Snow factor has already been taken into account. The solar glass used for the installation of flat plate solar collector is strong enough to withstand the extreme wind velocity and snow density.

It is also noted that operation of our solar dryer is not proposed during winter as there is non- availability of MAP's during extreme winter and snow falling season. MAPs collection and drying activity is from March-Oct which is highly available seasons from PSH point of view and also the MAP's availability. Meteorological conditions of District SWAT, SHANGLA, DIR are almost identical with little variations, therefore average values are considered in design and simulation of solar dryer.

6.4.3 Assessment of Drying Load

Major species of MAPs in project impact areas are 33 and harvesting period extends from April to December. Each UC has approximately 20 clusters and produce different quantities of various herbs per cluster. Some of these as below.

Table 6.6 Average Dryer Load In Each Union Council

88Botanical Name	Local Name	Average produce (kg/cluster)
Biostorta Amplexicaulis	Anjabar	300
Valariana Jatamansi	Mushk bala	200
Viola Spp (Flowers)	Banafsha	5
Berberis Lycium	Kwaray	20
Skimmia Laureola	Nazar pana	20
Aconitum Heterophyllum	Zaharmora	10
Paeoneaemodi	Mamekh	100

6.4.4 Proposed Design of Commercial Scale Solar Dryer

Proposed solar dryer consists of flat plat solar collectors and a room like drying chamber. A Main/primary duct for hot air from collectors, both roof and ground mounted. Hot air will mix with fresh ambient air by a solenoid valve at the inlet of dryer chamber. Hence we can adjust the mixing proportion of fresh and hot air according to temperature requirement of the dryer chamber and variations in ambient temperature.

Trays of wooden cover with galvanized iron mesh, arranged in columns are designed to place MAPs inside the dryer chamber. Several secondary distribution ducts arising from main duct are designed to supply hot air to each column trays.

A single drying chamber is designed for all species of MAPs, but an isolated chamber/column for products (like Musk Bala, podina) having volatile contents is designed within same chamber. After drying, humid and relatively cold air will leave the drying chamber through chimney. Exhaust fans and windows will ensure air ventilation throughout drying period. Air filter is installed at the inlet of dryer, so clean air circulates through product trays. This will ensure that MAPs being dried are hygienic and according to international health standards.

A biomass combustor needs to be provided to provide the hot air in case the solar insolence is not available due to clouds. Biomass combustor should be made of refractory bricks with metallic mesh grate to receive proper air for combustion from bottom side. This grate should be removable to remove ash intermittently. Refractory bricks ensure the heat to retain and properly diverted to flue gas to air heat exchanger for heating the air to be exposed to MAP's.

The separate closed tray rack will be provided a separate duct whereas the exit humid air leaving the volatile humidity will be separately connected to exit duct and discharged through main duct. It is to be made in order to ensure that the volatile matter is not mixed with the air in the drying chamber because it may change the medicinal properties of other species in the chamber

Digital gauges will record inlet, outlet and drying chamber temperature and air humidity. The designed solar dryer should be controllable in two ways i.e. either by changing the temperature of air entering the chamber (by opening or closing the solenoid valve to desired limit) or by varying the flow rate of hot air passing through the dryer. This will be helpful to set the dryer plant according to the need depending upon the humidity of Medicinal Plants. Following is the conceptual design of the solar dryer, providing the layout of its components.

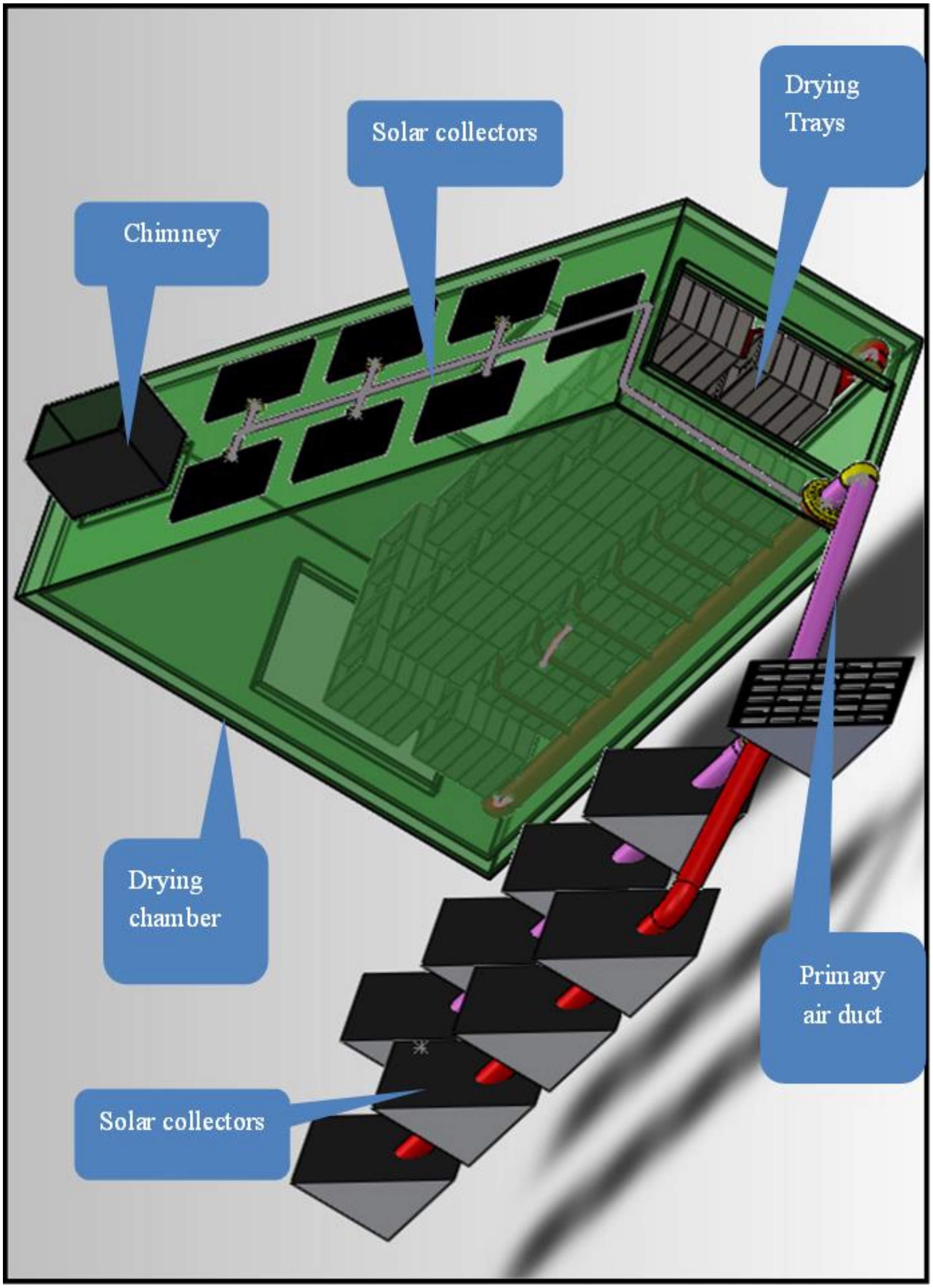

Figure 6.14 Conceptual Design Of Solar Dryer-Commercial Scale Model

6.5 Conclusion

On the basis of results obtained in this research, following points can be inferred:

- A detailed mathematical model for thermal analysis of flat plate solar air collector has been presented, and implemented by MATLAB.
- The numerical model and MATLAB algorithm can be applied for thermal analysis of various absorber materials, coatings and cover material as well.
- MATLAB code solves the model by using matrix inversion technique and iteratively evaluates the temperature histories for collector cover, absorber and outlet hot air at any time.
- CFD analysis of dryer chamber by Fluent software simulates the temperature variation along the chamber height during loaded and unloaded conditions.
- Experimental analysis proves a good agreement between measured and numerically predicted values. Hence MATLAB and Fluent simulation of solar collector and drying chamber respectively, provides sound estimation of thermal performance of solar dryer and help in design optimization.
- The designed solar dryer provides economical and efficient drying mechanism for drying of medicinal plants and herbs.
- Biomass hybrid system ensures more rapid and continuous drying of herbs. And heat exchanger prevents the smoke contamination in MAPs. So the dried products are according to quality standards.
- Temperature control mechanism effectively maintains the optimum drying temperature inside drying chamber.
- Based on this lab scale study pilot scale solar dryer can be proposed to dry large quantities MAPs on commercial scale.
- The designed hybrid solar dryer can be used to dry vegetables, fruits or other agricultural products.

6.6 Recommendations

- The exhaust fans can be driven from Solar PV panels, so the whole system would be independent from power source.
- Energy storage medium like PCM can be used to store solar energy during day time, so it can be utilized for drying at night time.
- Absorber plate of flat plate solar collector can be coated with selective coating like chrome coating to enhance the absorptivity.
- Length of Inlet pipes to the drying chamber should be minimized as possible to reduce the heat losses.
- Dehumidifier can be designed for the solar dryer, so that inlet air can be dehumidified up to the desired level. As humid air will affect the thermal performance of solar collector.
- Further experimental investigation is required to confirm the efficiency of designed heat exchanger.
- Further CFD analysis of dryer chamber is required to optimize the design.
- Automatic temperature control system can be designed by using automatic valves, actuators or stepper motor etc.

Summary

This chapter presents the results obtained from numerical simulation and through experimental analysis of designed solar dryer. Temperature of collector cover, absorber and outlet hot air were continuously measured from 8.am till 5.pm. Temperature variation inside the dryer chamber were monitored under loaded and unloaded conditions. Drying experiments were conducted for mint leaves under solar drying and biomass combustion as well. Comparative study proves good agreement between predicted and experimental results of thermal analysis. Commercial scale model of hybrid solar dryer for MAPs drying in northern areas of Pakistan has also been presented in this section, which is scale up model of designed solar dryer model. Important conclusion drawn from this study has been summarized along with recommendations for future research work.

Thermal Performance of Flat Plate Solar Air Collectors: Mathematical Model and Simulation

MariamMahmood[1*], Aftab Khan[2], Parvez Akhtar[1]

[1] Center for Energy Systems (CES), National University of Science and Technology (NUST),Islamabad, Pakistan.

[2] Department of Computer Systems Engineering, University of Engineering and Technology (UET), Peshawar, Pakistan.

*Corresponding author: mariammahmood294@gmail.com

Abstract

This paper presents a mathematical model and simulation algorithm to predict thermal performance of flat plate solar air collectors. Basic design and model of flat plate solar collector has also been discussed. Single air channel between the absorber and glass cover has been considered for thermal analysis. In mathematical model, temperatures of walls surrounding the air stream were assumed uniform for a short collector length.

A set of mathematical equations has been presented here to calculate heat losses of the collector, and mean temperatures of walls and air stream. Based on these equations, a simulation algorithm has been developed which involves matrix inversion technique in MATLAB software. An iterative process was then developed to compare the calculated mean temperatures with initially guessed values. Repetition of same iterative method for each hour enabled to calculate wall and air temperatures for the whole day.

Ambient conditions involved in calculation, have been reported from METEONORM global meteorological database for ISLAMABAD, PAKISTAN. But this is generalized simulation algorithm and can be extended to predict hourly thermal performance of flat plate solar collectors for any location's meteorological data.

Key Words: Ambient conditions, matrix inversion, iterations, mean air temperature.

1. Introduction

Rapid industrialization, urban sprawl, and swift economic growth are the chief driving factors for increased energy demand worldwide. Fossil fuels are prime energy source in global energy mix. But due to their detrimental environmental impacts and restricted supplies, there is dire need to harness enormous renewable energy potential that we are blessed with.

Solar heat is the most abundant among all renewable energy sources. The Sun radiates energy at the rate of $3.8*10^{23}$ kW, out of which $1.8*10^{14}$ kW is intercepted by our planet earth. After reflection into space and atmospheric scattering, about $1.08*10^{14}$ makes its way to the earth surface. If only 0.1% of this massive source is converted at 10% efficiency, it will generate four times the world's total generation capacity of 3000 GW [1]. On the other hand, periodic availability of sunlight and reliance on meteorological conditions are major impeding factors for its ample exploitation [2].

Solar air heaters employ solar radiation to heat air for many processes that involve low to medium temperature below 80^0C like crop drying and air conditioning [3]. Flat plate collectors consist of a top glass cover to transmit solar radiation towards the absorber plate that converts absorbed energy to heat, so increasing the enthalpy of air that flows through the air channel between absorber and cover, and bottom insulation to eradicate heat losses [4]. Apart from installation combination there are many other determinants of thermal performance of solar collectors: air flow rate, design and fabrication material of collector and prevailing meteorological conditions. A comprehensive study of all these factors is vital to optimize the system performance [5].

2. Objective

The objective of this study is to develop a mathematical model and simulation algorithm for reasonably accurate prediction of thermal performance of flat plate solar collectors, based on the ambient atmospheric conditions. Design and operation of solar collectors has also been briefly discussed.

3. Design And Mathematical Model Of Flat Plate Solar Air Collector

3.1 Basic flat plate collector consists of following main elements:

Transparent cover (glazing): To ensure maximum transmission of incoming solar radiation, glazing material should have high transmissivity (τ), high temperature stability, low absorptivity (α) and low reflection. Low iron content tempered glass is the most common glazing material for solar collectors as it has maximum transmissivity (0.85 -

0.90 at normal incidence) for incoming short wave radiation, but almost zero transmissivity for long wave radiation emitted by absorber.

Absorber: Absorber's prime function is to absorb maximum light transmitted through glazing, so to transfer the retained heat to the circulating fluid (water or air) with minimum losses to the surr3oundings. Most common materials used as absorber are copper and aluminum. Usually absorber plates are painted black (black paints for which α=0.92-0.98) to enhance their absorptivity.

Insulation: Flat plate collectors are insulated to minimize the conduction and convection losses from the bottom and edges of collector. Usually mineral wool, rock wool and glass wool are used as insulation [6].Main losses from flat plate solar collectors are optical and thermal losses. Optical losses are caused by reflection and absorption by transparent cover or due to less absorptivity of the absorber. While thermal losses are mainly caused by convection and conduction [7]. Flat plate solar collector with single air channel between top cover and absorber plate is being considered here for thermal analysis and development of a mathematical model.

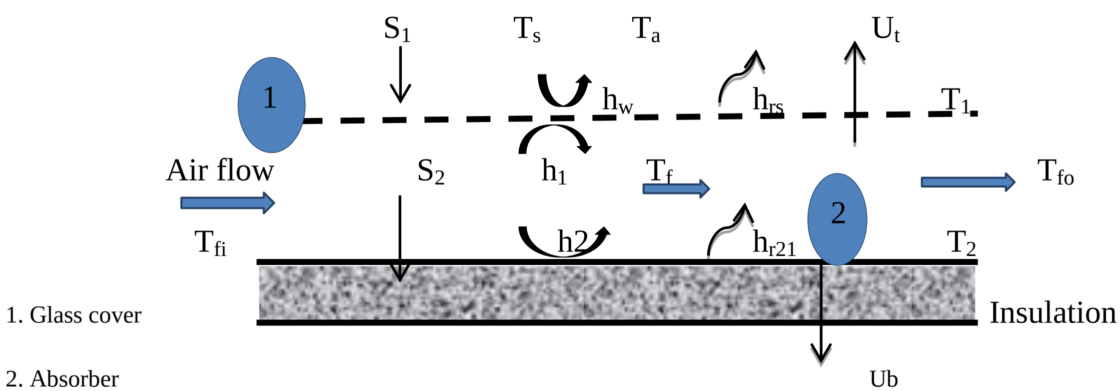

Figure 1 flat plate solar air collector- Thermal analysis

3.2Mathematical Model Development

3.2.1 Radiation Heat Transfer

The radiation heat transfer coefficient from top cover to the sky is:

$$h_{rs}= \sigma^* \epsilon_1(T_1+T_s)\,(T_1^2+T_s^2)\,(T_1-T_s)/(T_1-T_a) \qquad (1)$$

When $T_a = T_s$ equation (1) becomes

$$h_{rs}= \sigma^* \epsilon_1(T_1+T_s)\,(T_1^2+T_s^2) \qquad (2)$$

Radiation heat transfer between cover and absorber (1 and 2) is:

$$h_{r21}= (\sigma *(T_1^2+T_2^2) (T_1+T_2)) / (1/\epsilon_1+1/\epsilon_2 -1) \quad (3)$$

3.2.2 Convection Heat Transfer Due To Wind

Convection heat transfer coefficient from top cover due to wind is:

$$h_w = 5.7+ (3.8)*V \quad (4)$$

Where V is wind speed.

3.2.3 Forced Convection Heat Transfer Between Cover And Absorber

Air flow between cover and absorber can be laminar, transition or turbulent, which can be determined from Reynolds number (Re).

$$Re=(\dot{m}*D_h)/(A*\mu) \quad (5)$$

Laminar flow: if Re is < 2300, air flow is laminar. Nusselt number is then calculated as

$$Nu=Nu_{infinity}+(Nu_1)/ (Nu_2). \quad (6)$$

Where

$Nu_1= a*[Re*P_r*(D_h/L)]^m$, $Nu_2=1+b*[Re*P_r*(D_h/L)]^n$

And constants are:

a=0.0019; b=0.00563; m=1.71; n=1.17; $Nu_{infinity}$=5.4(for P_r = 0.7)

Turbulent Flow:

If Re is > 6000, air flow is turbulent. Nusselt number is calculated as:

$$Nu=0.023*Re^{0.8}*[Pr^{0.4}] \quad (7)$$

Transition flow: if 2300< Re<6000 then air flow is in transition region. Nusselt number is calculated as:

$$Nu= 0.116*(Re^{0.68}-125)*(P_r^{0.33})*(1+ (D_h/L)^{0.68}) \quad (8)$$

Based on Nusselt number calculated as above (which ever case applies) convection heat transfer coefficient is calculated as:

$$h=Nu*K/D_h \quad (9)$$

Where D_h is hydraulic diameter.

It is assumed that convection heat transfer coefficient from cover to air (h_1) and from absorber plate to air stream (h_2), both are equal. Thus

$$h_1=h_2=h$$

3.2.4 Solar Radiation

Solar radiation flux absorbed by top cover is:

$$S_1 = \alpha_1 * H \qquad (10)$$

And by absorber plate:

$$S_2=\tau*\alpha_2 * H \qquad (11)$$

3.2.5 Overall Heat Loss Coefficients

Overall heat loss coefficient from top surface is:

$$U_t= h_w + h_{rs} \qquad (12)$$

And for bottom heat loss:

$$U_b = 1/ [(x_{bi}/ k_{bi}) + (1/h_w)] \qquad (13)$$

4. Simulation Procedure

The theoretical model assumes that:

e) Temperature of the walls (cover and absorber) surrounding the air stream are constant for a short collector.

f) Heat losses from collector edges are negligible.

g) Properties of collector material (cover, absorber and insulation) are independent of temperature.

The algorithm to calculate cover temperature, absorber and mean air temperature at collector outlet for each hour of the day is as follows:

For first hour: wall and mean air temperatures are assumed equal to the ambient temperature, and heat transfer coefficients are calculated by using above equations. Then following matrix is developed:

$$\begin{bmatrix} (h_1 + h_{r21} + U_t) & -h_1 & -h_{r21} \\ h_1 & -(h_1 + h_2 + z) & h_2 \\ -h_{r21} & -h_2 & (h_2 + h_{r21} + U_b) \end{bmatrix} \begin{bmatrix} T_1 \\ T_{fo} \\ T_2 \end{bmatrix} = \begin{bmatrix} U_t T_a + S_1 \\ -(z * T_{fi}) \\ S_2 + U_b T_a \end{bmatrix}$$

Where $z = 2\dot{m}C/WL$

It can be written as: $[A]\,[T] = [B]$ (14)

Here mean temperatures [T] is calculated by using matrix inversion method in MATLAB software.

$$[T] = [A]^{-1}[B]$$

Now compare these newly calculated values with previously assumed values of wall and air temperatures, if difference is less than 0.01 then replace new values with assumed values, if not repeat same calculations and find T matrix again. In this way an iterative procedure is repeated until all consecutive values of temperatures differ by less than 0.01.

For 2nd hour: replace wall temperatures (T_1 and T_2) with respective values of previous hour, and inlet air temperature equal to ambient temperature of this hour. Repeat same iterative procedure and calculate T matrix.

In this way mean temperatures of all hours in a day or a month can be predicted for given collector. MATLAB algorithm based on above iteration procedure is shown in a flow chart (Fig.2)

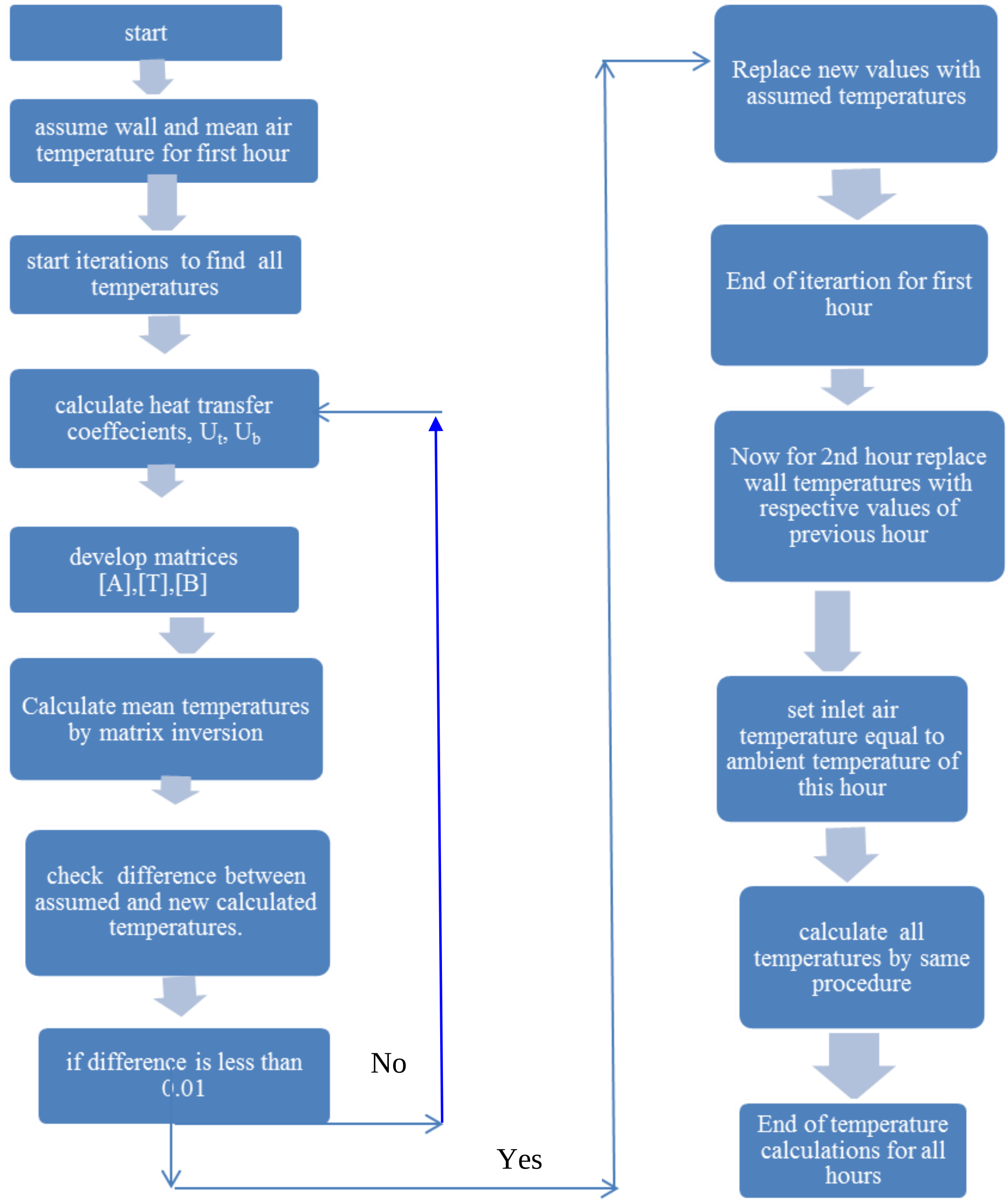

Figure 2 Simulation Algorithms for Thermal Analysis of Flat Plate Collector

5. Results

To predict mean temperatures for a flat plate solar air collector, simulation was performed for a short collector length. Parameters assumed in calculations are as follows:

Air mass flow rate ($\dot{m}$) = 0.02 kg/s. Emissivity of top glass surface = ϵ_1 =0.88

Emissivity of absorber = ϵ_2 = 0.12. Absorptivity of top glass cover = α_1 = 0.06

Absorptivity of absorber = α_2 = 0.95. Transmissivity of the top glass cover = τ= 0.84

Thermal conductivity of bottom insulation = k_{bi} = 0.03 W/m-k

Ambient conditions for ISLAMBAD, PAKISTAN were reported from METEONORM global meteorological database. However this simulation procedure can be used for any ambient conditions and collector specifications. Simulation results performed for single air channel are presented below. Simulation results indicate that increasing the air flow rate decreases the mean air temperature, if all other operating conditions are kept constant. Ambient conditions also affect mean wall and air temperatures. But in all cases it is evident that absorber plate exhibits the highest temperature, while cover and air temperature differ slightly (Figs 3-6).

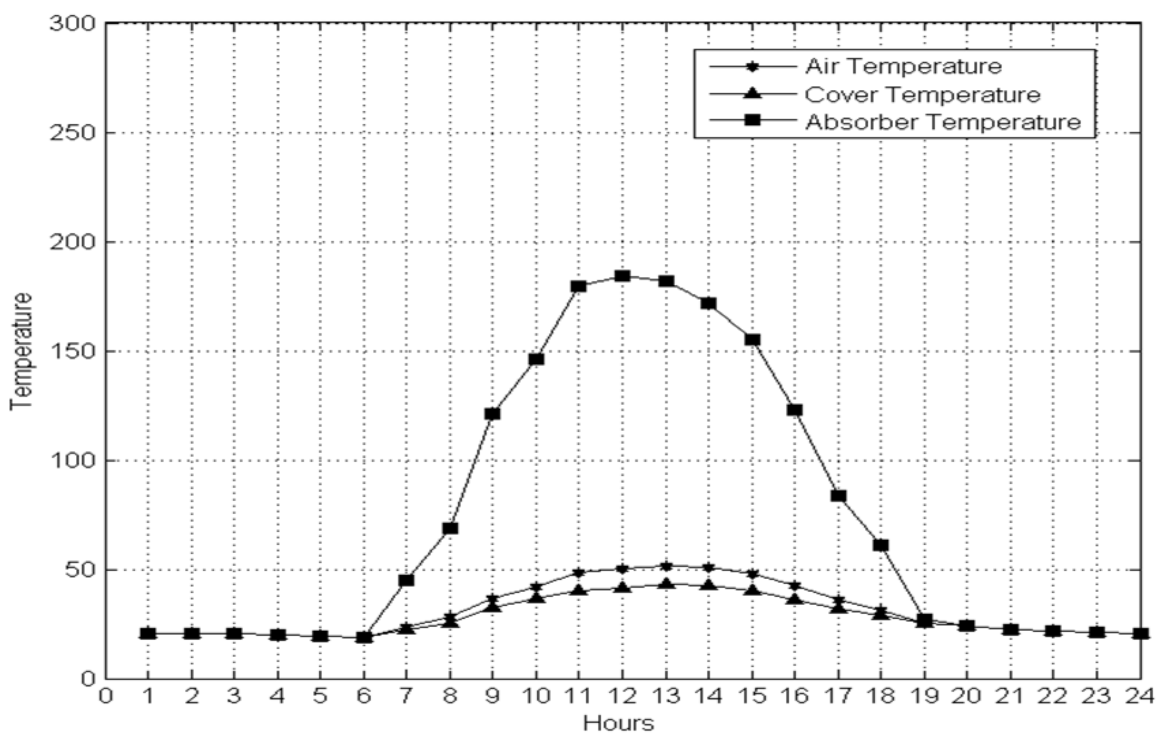

Figure 3 - Hourly Temperature variation on 15th April, air flow rate=0.02kg/s.

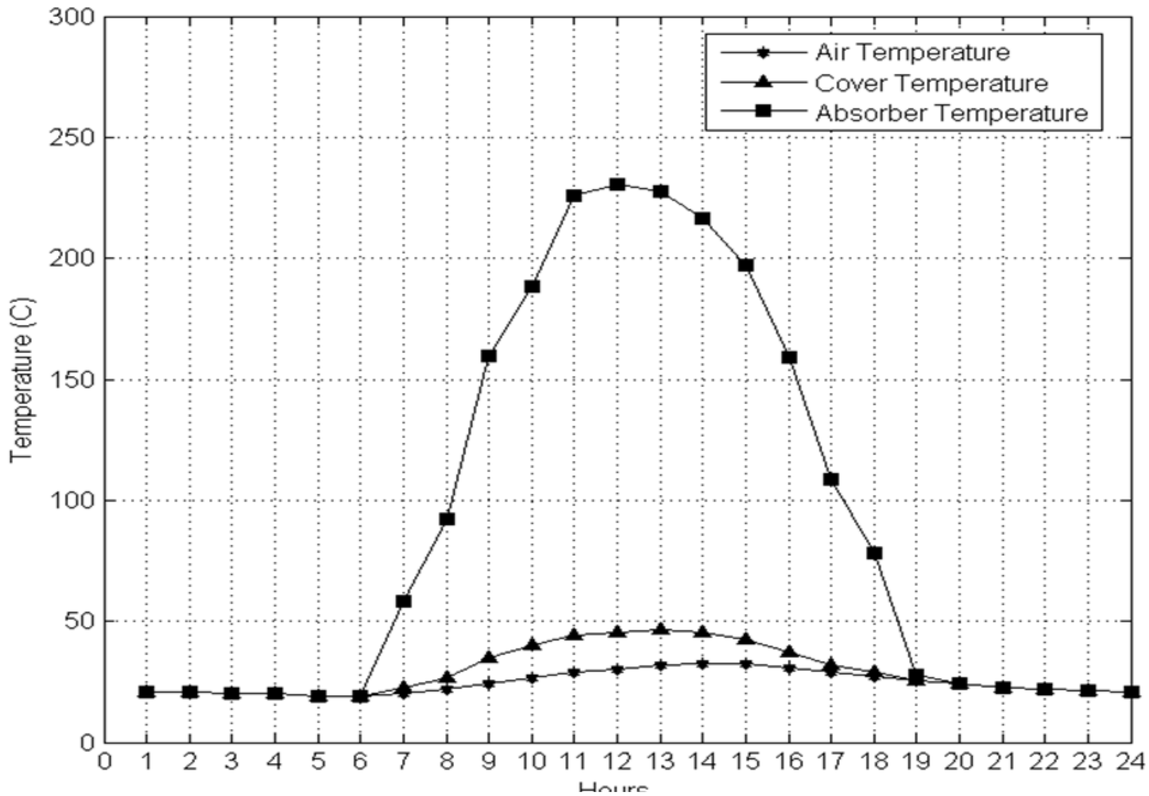

Figure 4- Hourly Temperature variation on 15th April, air flow rate=0.5kg/s.

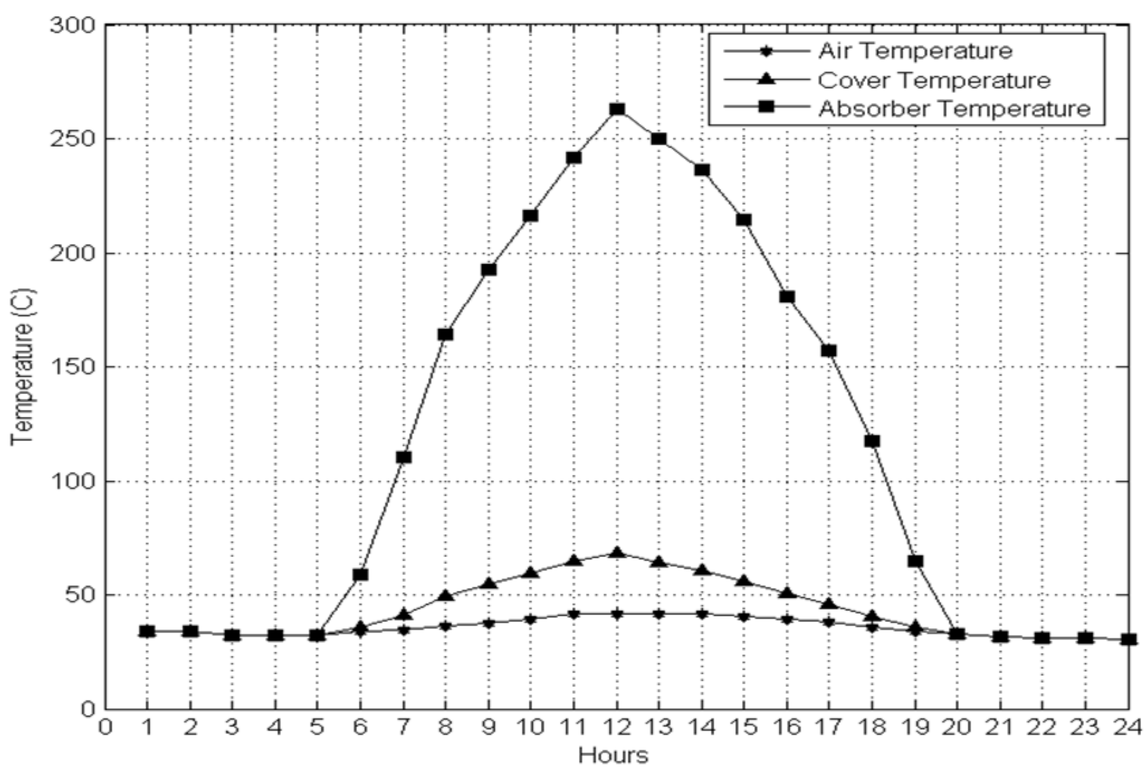

Figure 5- Hourly Temperature variation on 15th June, air flow rate=0.02kg/s.

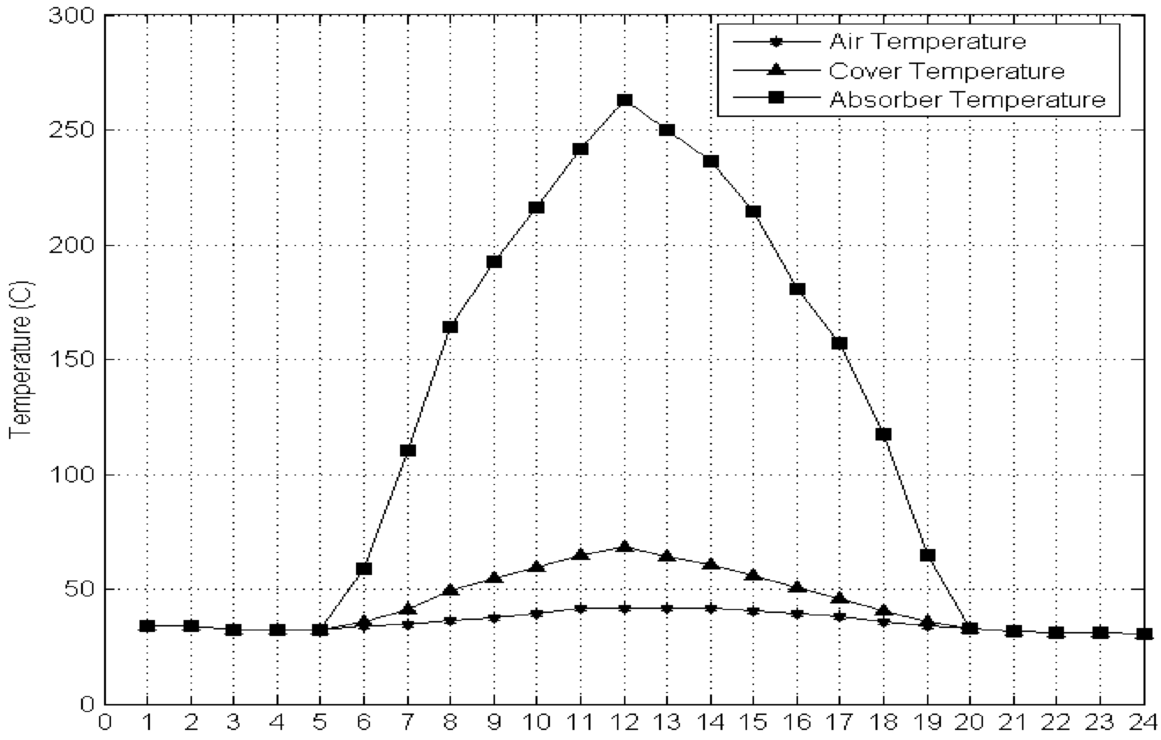

Figure 6 - Hourly Temperature variation on 15th June, air flow rate=0.5kg/s.

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Experimental Assessment of an Indirect-Mode Forced Convection Solar Dryer for Drying Herbs

Mariam Mahmmod[1]*, Mohammad Ahsan[1], Parvez Akhter[1], Ahmad Sohail[2]

1. Center for Energy Systems (CES), National University of Science and Technology (NUST), Islamabad, Pakistan.
2. College of EME, National University of Science and Technology (NUST), Islamabad, Pakistan.

*****corresponding author: mariammahmood294@gmail.com

Abstract

This paper presents the performance evaluation of an indirect-mode forced convection solar dryer for drying herbs and medicinal plants. The system was experimentally investigated under Islamabad (33.7167° N, 73.0667° E) prevailing ambient conditions. The dryer consists of a single-glazed flat plate solar collector, drying chamber and a fan. Hot air from solar collector is forced into the drying chamber through a duct from bottom inlet, where it absorbs moisture from the products and then moist and relatively cold air exits through top outlet. The dryer was tested to dry mint leaves (initial moisture content 85%) under the ambient temperature of 30^{o}C, and average daily global radiation range of 200-800W/m^2 on horizontal surface. Total drying time to dry 2kg mint leaves was 8-9 hours approximately, under the flow rate of 0.01kg/s. Products dried in the solar dryer are protected from dust, rain and insects, so the designed solar has potential applications in herbs drying.

Key words: absorber plate, forced convection, flow rate, moisture content, solar drying.

1. Introduction

Drying is the first and most essential step in post-harvest processing of herbs or medicinal plants and for their long term preservation. Drying is defined as: ‘the process of reducing the plants’ natural moisture content up to stable or equilibrium moisture content to prevent the enzymatic and microbial activity’. Consequently it increases the shelf life of plants for the long term preservation. Drying also assists in transport and storage of plants due to reduction in volume and weight. Consequently it contributes to supply chain and marketing of medicinal plants [1]. Drying process of herbs must fulfil the following requirements in order to preserve the quality of dried products:

1. Moisture content must be reduced up to an equilibrium level defined by storage standards for certain temperature and air humidity.
2. Colors, flavors, aroma and active ingredients need to be preserved with no or minimum deterioration.
3. Microbial count must be below the standard limits, and without applying any chemical additives.

In developing countries herbs are mostly dried by traditional methods such as open sun drying or drying in the shade, without using supplementary energy source.

These methods have many draw backs like:

1. Direct exposure to intensive solar radiations has adverse effects on quality of herbs, thus causing loss of active ingredients and essential oils.
2. Ambient conditions such as high temperature and air humidity promotes mold development and microbial activity which hinders the long term preservation of herbs.
3. Traditional drying methods cannot handle large capacity.

Thus to achieve final dried products of international pharmaceutical standards, modern technical drying systems such as solar dryers are indispensable [2].Hence solar dyer is vital to overcome these problems of sun drying, as it traps the radiative heat judiciously and ensures the product quality [3].

Solar dryer accelerates the drying process by supplying more heat, which results in increased vapor pressure of product moisture content and decreased relative humidity of air, which in turn increases the moisture loading capacity of air. In this way solar dryer ensures efficient drying mechanism [4].

To preserve the active ingredients and essential oils within medicinal plants, low drying temperature (around 50-60^{o}C) is recommended, thus it prolongs the drying duration. Drying process incurs 30-50% of the total processing cost of medicinal plants. Thus it is critical to identify the factors responsible for high cost.

One of the substantial factors is energy demand of drying process, which has tremendously increased due to high prices of conventional fuels. Moreover drying parameters like dryer design, optimum drying temperature and humidity, operational method and supplement energy source are very critical and influential in terms of quality of herbs. Thus these require extensive research and crucial monitoring to get the dried herbs of international pharmaceutical standards [5].

Pakistan, being located in the sunny belt, has immense potential of solar energy. And this source is abundantly available all across the country. The country receives average global irradiation of 200-250 Watt/m^2-day, with about 1500-3000 sunshine hours per annum. Despite of these ideal conditions, we are unable to exploit solar energy at its full, and use of solar energy for power generation or heating is still in infancy. Solar thermal energy can find potential applications in drying of agricultural products and medicinal plants by using solar dryers. Due to escalating prices of fossil fuels and their dwindling supply, solar drying is the best alternative to conventional fuel drying [6].

The main objective of present work is to develop an indirect-mode forced convection solar dryer for drying herbs, and to investigate its thermal performance.

2. Design of The Solar Dryer

The solar dryer designed and investigated in this study, essentially consists of a flat plate solar collector, drying chamber and a fan.

For the flat plate solar air collector, a v-corrugated aluminum plate of 0.001m thickness and $1\times0.5m^2$ area was used as the absorber plate. This was painted black to enhance the absorptivity. A glass sheet of 0.004m thickness was used as top cover (glazing) to transmit the absorbed radiation to the absorber and minimize the heat losses. The gap between the absorber plate and glass cover (0.025m) serves as the air channel [Fig.1]. The collector was insulated from all sides using 0.05m thick glass wool as an insulating material. The overall length, width and height of solar collector are 1m, 0.5m and 0.25m, respectively.

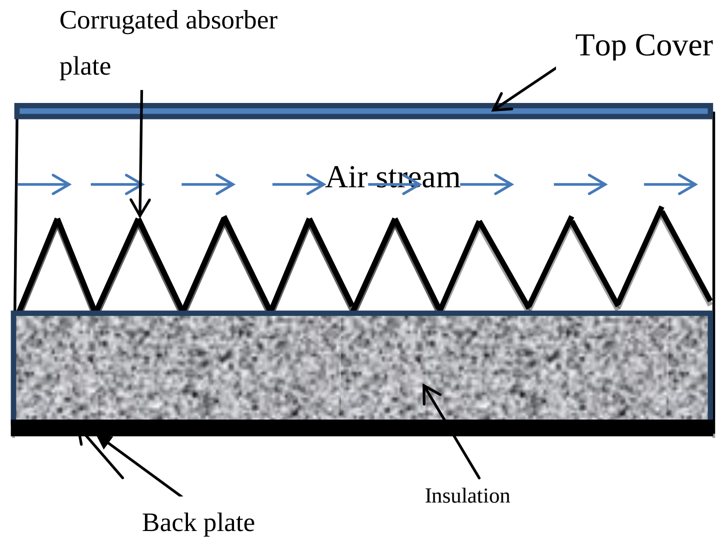

Figure 6.1. A schematic diagram of flat plate solar air collector

Dryer chamber was fabricated from GI sheet (18gauge) and insulated from all sides with 0.03m thick glass wool. Three perforated drying trays constructed from 0.003m mesh stainless steel screen, were contained inside the chamber with equal vertical spacing of 0.15m. Each tray has an area of 0.3×0.3m2, placed on a wooden frame fixed to the inner walls of the chamber. Drying trays were fixed through sliding channels so trays can be removed easily through a front door. The overall length, width and height of dryer chamber are 0.4m×0.4m×0.6m, respectively.

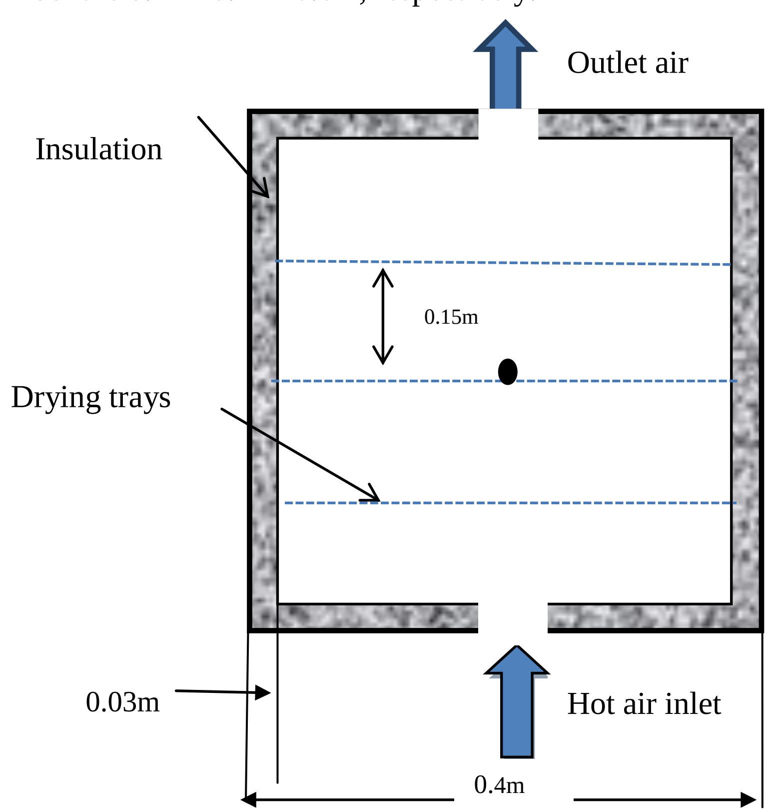

Figure 6.2. A Schematic Diagram of Dryer Chamber

To force the hot air from solar collector to the drying chamber, a 20- CFM (1.5W) fan was installed at the outlet of solar collector. Hot air from the collector is forced into the drying chamber through a pipe/duct. Hot air enters the chamber from bottom, moves through the product trays, picks up the moisture and exits through chimney at the back side of chamber.

3. Drying Analysis

This section deals with the fundamental principles and equations governing the drying process [7], [8],[9].

Moisture content on dry basis (M_{od})

M_{od} is the weight of moisture present in the product per unit weight of the dry product:

$$M_{od} = \frac{(Wo - Wd)}{Wd} \qquad (1)$$

The initial moisture content on wet basis M_{ow} is:

$$M_{ow} = \frac{(Wo - Wd)}{Wo} \qquad (2)$$

The instantaneous moisture content (M_t) on dry basis at any time t is calculated as follows:

$$M_t = \frac{(Mod + 1)Wt}{Wo} - 1 \qquad (3)$$

The moisture content on wet and dry basis is related as:

$$M_w = 1 - \left(\frac{1}{(Md + 1)}\right) \qquad (4)$$

The moisture ratio (MR) is defined as:

$$MR = \frac{(Mt - Me)}{(Mo - Me)} \qquad (5)$$

Efficiency of solar collector is calculated as:

$$\eta = \frac{Q}{IA} \qquad (6)$$

Where I is the solar radiation energy flux (W/m^2) calculated by pyranometer, Q is thermal energy transferred to the air stream and calculated as:

$$Q = \frac{\dot{m}Cp}{(Ti - To)} \quad (7)$$

4. Experimental Investigation of Dryer Performance

The instruments used for experimental evaluation of solar dryer are as follows.

A. Instruments

To measure the air temperature at collector outlet and in drying chamber, thermocouples of type K were used. Relative humidity of ambient air and drying air was measured using hygrometer (model MS1). To measure the weight of products during drying procedure, a digital balance with least count of 0.001g was used, and monitored the mass loss of products after every 60 minutes during the drying experiment. The average global radiation on a horizontal surface was measured using a pyranometer (Kipps, model CM3). A data logger ((Yokogawa, model DC100) was used to record temperature and solar radiation data from pyranometer and thermocouples, respectively. All the experiments were continued until the drying products achieved their equilibrium moisture content.

B. Drying Procedure

To assess the thermal performance of indirect-mode forced convection solar dryer, drying tests were carried out for drying mint leaves in May 2014, under Islamabad (33.7167° N, 73.0667° E) prevailing ambient conditions. Prior to drying process, products were washed and dried manually, and then sliced into same size to ensure the uniform drying. For drying test the dryer was manually loaded with products, and during drying procedure the products were stirred manually two or three times per day to ensure the uniform drying.

5. Results And Discussion

The variation of moisture content of mint leaves during drying procedure is presented in Fig.3. Results have been recorded for drying 3kg mint leaves under the ambient temperature of 30-35 ^{o}C, and air mass flow rate of 0.01kg/s. Initially drying rate is rapid, because of excess moisture on the product surface. Part of the heat from flowing air is used to evaporate surface moisture content, while remaining heat is transferred to the product interior. Thus product temperature rises and moisture from the inner start evaporating. Drying during this stage is slower comparatively, as moisture is trapped inside the product. It is evident that total time to dry mint leaves from initial moisture content of 85% to 11% is 9hrs, approximately.

Moisture ratio was calculated using equation (5) and variation of MR versus drying time is presented in Fig 4. This also shows descending trend like moisture content. Solar collector efficiency calculated from equation (6) was found to be 24.0%, under the average global radiation of 700 W/m^2.

Fig.5 shows the air temperature variation at collector outlet and at the middle of drying chamber. Maximum air temperature up to 62^{o}C, is achieved at noon (around 1 pm), when collector receives maximum solar radiation intensity. Because of heat losses in the air duct, air temperature inside the drying chamber is 10-15^o C lower than collector outlet.

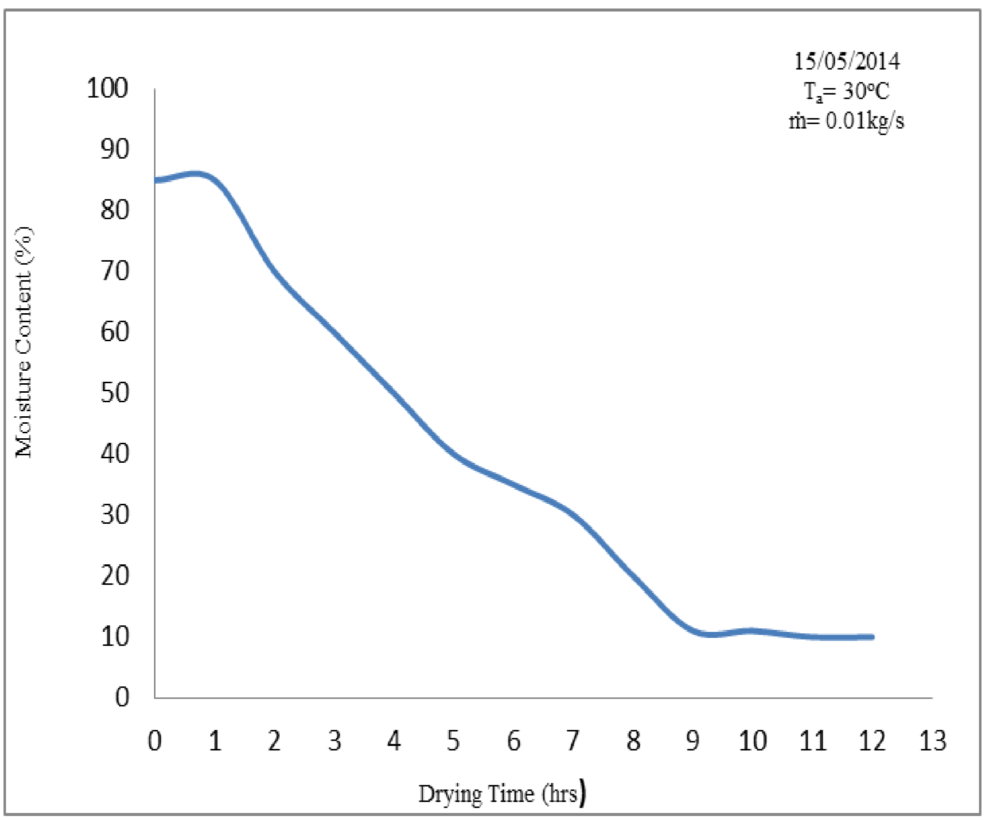

Figure 6.3. Variation of Moisture Content of Mint Leaves with Drying Time

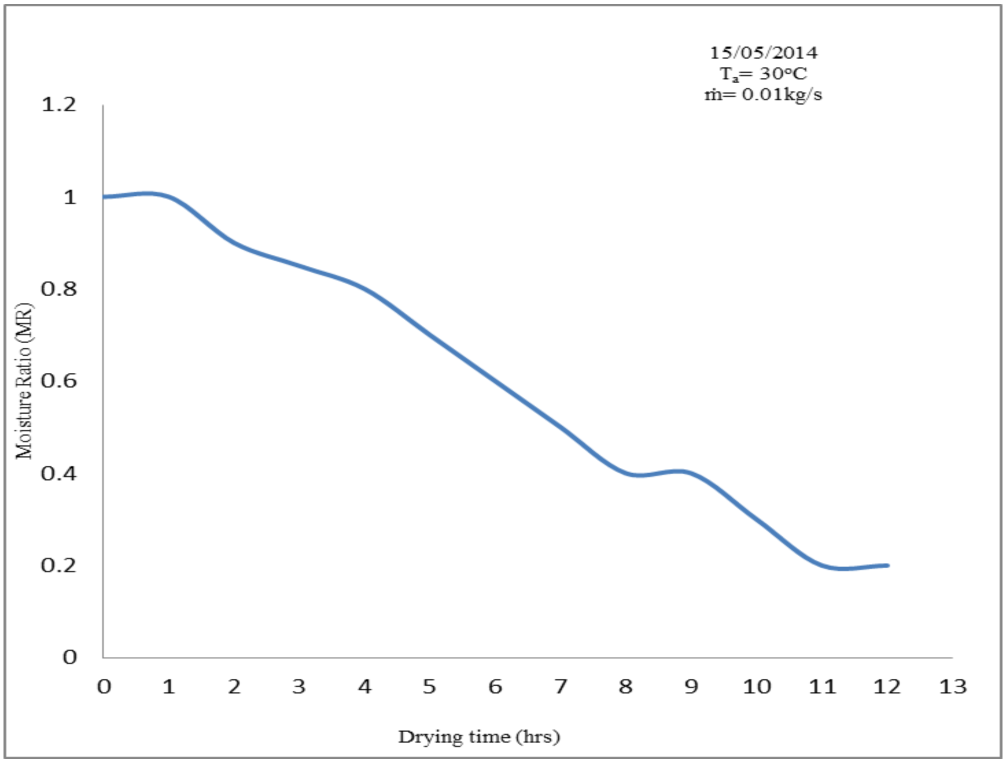

Figure 6.4. Variation of Moisture ratio of mint leaves versus Drying Time

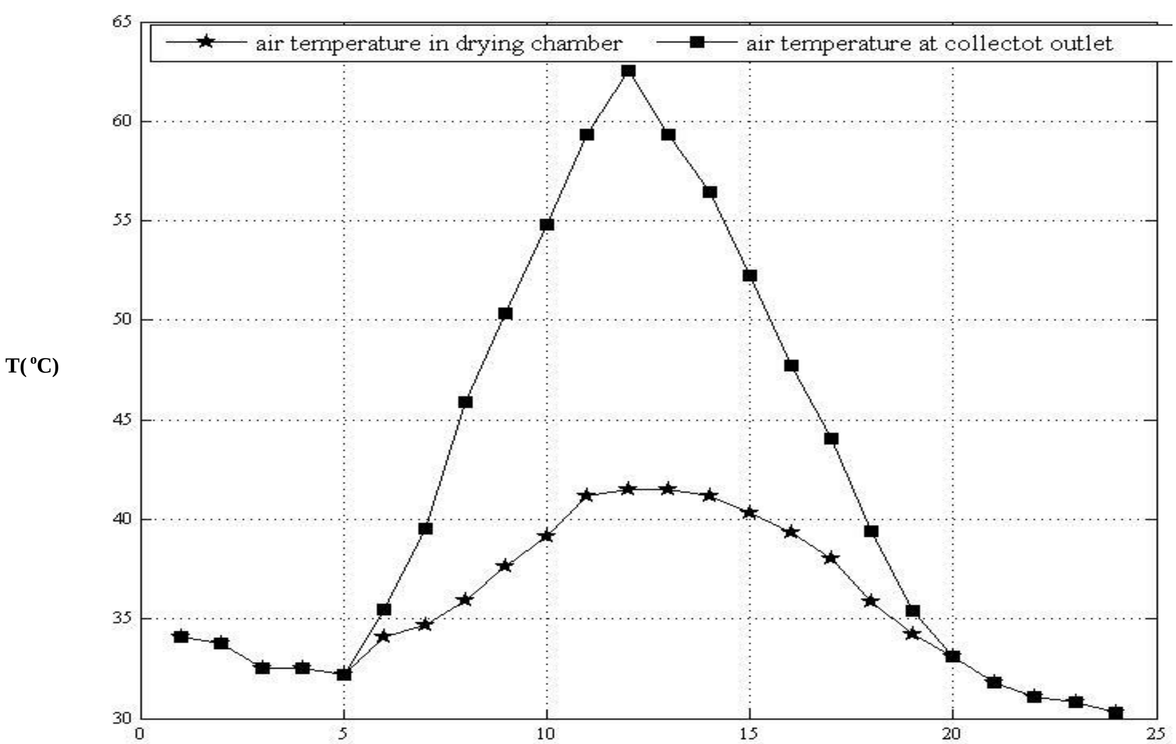

Figure 6.5. Air temperature at collector outlet and drying chamber

Conclusion

The construction and performance evaluation of an indirect- mode forced convection solar dryer has been carried out under ambient conditions. Solar collector efficiency was found to be 24.0%, under the average global radiation of 700 W/m^2. And peak air temperature at collector outlet was around 62^oC. The designed solar dryer system is useful for drying of herbs, medicinal plants and other crops which need to be protected from direct exposure to solar radiation. Further research work is in progress to maximize the drying efficiency and minimize the heat losses.

Nomenclature

W_o Initial weight of the product (kg)

W_d Weight of the dried product (kg)

W_t Weight of the product at any time (kg)

M_o initial moisture content (dimensionless)

M_e Equilibrium moisture content (dimensionless)

A Area of solar collector (m^2)

$\dot{m}$ Air mass flow rate (kg/s)

C_p Specific heat capacity of air (kJ/ kg-k)

T_o Air temperature at collector outlet (k)

T_i Air temperature at collector inlet (k)

η Collector efficiency

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