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(including CLIMATE CHANGE)

# Master Dissertation

Submitted in partial fulfillment of the requirements for the Master degree in

[Energy Engineering]

Presented by

***Rana Mamdouh Mostafa Ismail AWAD***

## Design a solar dryer with integrated thermal storage based on sorption materials

***Defended on 04/09/2019 Before the Following Committee:***

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# DECLARATION

I, **Rana Mamdouh Mostafa Ismail Awad** do hereby declare that this thesis is my original work and to the best of my knowledge, it has not been submitted for any award in any University or Institution.

Signed_____Rana Mamdouh __________________________Date______11/8/2019_______

# CERTIFICATION

This thesis has been submitted with my approval as the supervisor

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# ABSTRACT

Solar drying is not modern technology, but it is a traditional way to save nutrition so it can be consumed later. Dried mangoes were introduced as an idea that it will develop an added value for the mangoes in West Africa and Burkina Faso where there is massive production. The target group was the small mangoes producers and companies. Non-governmental organizations (NGOs) distributed solar dryers on women, and they conducted training for them. By the time the solar dryer seemed to be inefficient, the majority left it, and the companies now are using gas-fired dryers for drying mangoes.

Burkina Faso is not a gas producer county, and it imports it from the Codivoir, the gas price is quite high even that it is subsidized. It represents 15 -30 % of the total cost of the drying process. It is known that the national strategy is about removing natural gas subsidies, which will make the drying activity unprofitable according to mangoes producers.

Since Burkina Faso has abundant solar irradiance, it is preferable to utilize it in drying mangoes. Some models were developed for solar dryers for mangoes in the past, but none of them is working. The reason is the climate conditions in the harvesting season of mangoes, relatively high relative humidity of the air combined with relatively low solar radiation.

Sorption material is the technology is being used nowadays to perform high-density energy storage. The addition of such thermal energy storage can be part of the solution because it will absorb the excess humidity in the air, which will enhance the air capability to absorb the moisture in the mangoes. Also using storage will increase the working hours by storing the available solar irradiance and using them at night.

# RÉSUMÉ

Le séchage solaire n'est pas une technologie moderne, mais c'est une façon traditionnelle d'économiser la nourriture pour qu'elle puisse être consommée plus tard. Les mangues séchées ont été introduites comme une idée qu'elles développeront une valeur ajoutée pour les mangues en Afrique de l'Ouest et au Burkina Faso où il y a une production massive. Le groupe cible était les petits producteurs et entreprises de mangues. Les géocroiseurs ont distribué des séchoirs solaires aux femmes et ont organisé une formation à leur intention. Mais lorsque le séchoir solaire a semblé inefficace, la majorité l'a quitté et les entreprises utilisent maintenant des séchoirs au gaz pour sécher les mangues.

Le Burkina Faso n'est pas un pays producteur de gaz et l'importe de la Côte d'Ivoire, le prix du gaz est assez élevé même s'il est subventionné. Il représente 15 à 30 % du coût total du processus de séchage. On sait que la stratégie nationale consiste à supprimer les subventions pour le gaz naturel, ce qui rendra l'activité de séchage non rentable pour les producteurs de mangues.

Comme le Burkina Faso dispose d'un rayonnement solaire abondant, il est préférable de l'utiliser pour le séchage des mangues. Il ya quelques modèles ont été développés pour les séchoirs solaires pour les mangues dans le passé, mais aucun d'entre eux ne fonctionne. La raison en est les conditions climatiques de la saison de récolte des mangues, l'humidité relativement élevée de l'air et le rayonnement solaire relativement faible.

Le matériau de sorption est la technologie utilisée de nos jours pour effectuer le stockage d'énergie à haute densité. L'ajout d'un tel stockage d'énergie thermique peut faire partie de la solution parce qu'il absorbera l'excès d'humidité dans l'air, ce qui améliorera la capacité de l'air à absorber l'humidité dans les mangues. L'utilisation d'un accumulateur augmentera également les heures de travail en stockant le rayonnement solaire disponible et en l'utilisant la nuit.

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# CHAPTER ONE: INTRODUCTION

## 1.1 Introduction

In this part, an overview of the drying process as a solution to preserve the products for long term, the status of mango drying activity is represented, the issues facing solar dryer promotion are highlighted.

## 1.2 Background Information

The drying technique is an incent way to keep foodstuff like fruits, vegetables, meat, and fish, for an extended period. It was done by spreading the vegetables in the ground outside for some time.

The drying process is about removing the unwanted moisture inside fruits, this often done using dryers which can differ in terms of the design, the loading capacity and the energy used in the process like gas, electricity and solar. Gas dryers burn fossil fuel to heat the air being used to remove moisture content. it is a source of carbon dioxide, and it pollutes the environment. In the context of the majority of the African countries, the gas dryer is not preferable because of the gas price. The case of electric energy dryers is not far from the gas dryers because also electricity prices are high, it is not available everywhere, so this limits the usage. Although, electric energy dryer is efficient, it requires less operating hours and almost zero emissions. Solar dryer seems more suitable for the African countries where there are abundant radiations. Its simple technique so locals can work on it without prerequisite training. The activity capital cost is not that high so that it can be economical.

The primary constraint in solar dryers' usage is the internment nature of solar energy, so having storage is critical technology. It will convert solar dryers from small scale systems for a family to a large scale system for an enterprise. Sorption materials are a promising technology, and there are many researches are done in defining the sorption ability to store the thermal energy. In this thesis, we are focusing on solar dryer designs with built-in thermal storage.

## 1.3 Problem Statement

Burkina Faso is a mango producer country with annually production ranges of 154000 – 252000 t [1]. This vast amount is worth but not in Burkina Faso. There are only four marketing channels for the mangoes, selling it in the local market, exporting fresh mangoes, making juice for local use and exportation and exporting dried mangoes. The lack of marketing channels and other factors leads to significant losses, according to some studies the losses are 50 % from the annually production [2].

Since Burkina Faso depends on agriculture as national income, and 29 % of the population works in this field [3] , so developing an added value for the mangoes can improve the standard of living of a good percentage of the country population, it works for poverty reduction.
Some NGOs introduced dried mangoes activity, and they distributed some solar dryers. Nowadays, the dried mangoes sector generates € 46 million annually [1], but the shear of solar dryers in generating this profit is so limited compared to natural gas dryers. The used dryers are natural gas-fired dryers [4]. The main obstacle to the upscale gas-fired dryer is the gas prices, which represents 15- 30 % from the drying activity cost. Burkina Faso is not a natural gas producer country; it imports mainly from Ivory coast. From time to time, there is a shortage in the gas. By analyzing the national plan, there is an approach to remove the gas subsidies, which will make the activity unprofitable according dried mangoes producers.

However, solar energy is a free source of energy and a clean source compared to fossil fuel. In the context of Burkina Faso, the average annual solar irradiation is 19.8 MJ/m$^2$ per day [5]. The implementation of solar dryer is facing technical issues because the mangoes harvesting season is the rainy season, the climate conditions lead to long operation time three days instead of 8 hours for gas-fired. Besides, it seems uneconomic due to low capacity, which accompanied by a low drying rate.

## 1.4 Research Questions and The Working Hypothesis

What would be the best design for the solar drying system in the context of Burkina Faso?

Could a sorption bed play the role of an air-drying booster and thermal storage, allowing drying at night-time significantly increase the performance of a solar dryer, especially during rainy seasons?

Could the available solar radiation be enough for the sorption material regeneration, considering the rate of both regeneration and adsorption?

## 1.5 Research Objectives

Develop a static design for a solar drying system with built-in thermal energy storage for mangoes in Burkina Faso.

### 1.5.1 Specific objectives

- Determine the solar dryer type that matches the local context.
- Determine the optimal thermal storage technology to be used.
- Select suitable sorption material for energy storage.
- Propose an initial design for a solar drying system.
- Suggest the material to be used for dehumidification.
- Design the dehumidifier in the drying system.
- Sizing the drying system solar air collector.
- Calculate the thermal storage required capacity.
- Simulate the required sizes of the proposed solar dryer; a year-round simulation performed using weather data corresponding to the tropical wet and dry climate in West Africa (typically Bankandi, Burkina Faso)
- Edit the initial design of the solar dryer based on simulation results.

## 1.6 The Scope of the Study

A review will be conducted to determine the status of the solar dryers in the field. The available designs, their capacities. Another review for solar dryer designing trials which were done in Burkina Faso, neighboring countries, and all over the world will be demonstrated. A new design for a solar dryer with dehumidifier and built-in thermal storage will be suggested. Using the climate data of the cultivating region, the system parts will be sized. Review on the sorption material and regeneration technologies will be done. The different sorption material will be compared to decide the optimal for the suggested solar drying system design. Insight for the regeneration process requirements in the different sorption materials

# CHAPTER TWO: LITERATURE REVIEW

## 2.1 Solar Dryers

Dried food is not modern technology but an old technique for long-time preservation. According to some statistics, crop losses can reach 50 % due to post-harvesting, lack of marketing channels, and inappropriate preserving techniques [6] . With the global trend to save the environment and to achieve sustainability, the usage of renewable energy resources had been enlarged, especially solar energy. The advantage of solar energy compared to other renewable resources is that the potential is available almost everywhere. Furthermore, the solar potential is very high on the African continent. Drying foodstuff using sun radiation is locally done, but it has many disadvantages like long drying period, which leads to the possibility of bacteria development in the plant. Designing an efficient solar dryer in some context is an exciting challenge because of the climate conditions.

Solar dryer technology can help in solving the global food problem. Dried cereals can be food to millions of peoples who suffer hunger all over the world. Dehydrating vegetables and fruits keep them and in the meantime, reduce their weight, so it becomes more easy to transport them. In the African continent, dried herbs and plants is a way to achieve food security, and it is a source of income for people by selling them.

## 2.2 Solar Dryers Working Principle

Solar dryers use solar energy to evaporate the unwanted moisture content from vegetables and fruits. According to the system operation, solar dryers can be classified into direct, indirect mixed mode and hybrid as shown in Figure 1**Error! Reference source not found.**.

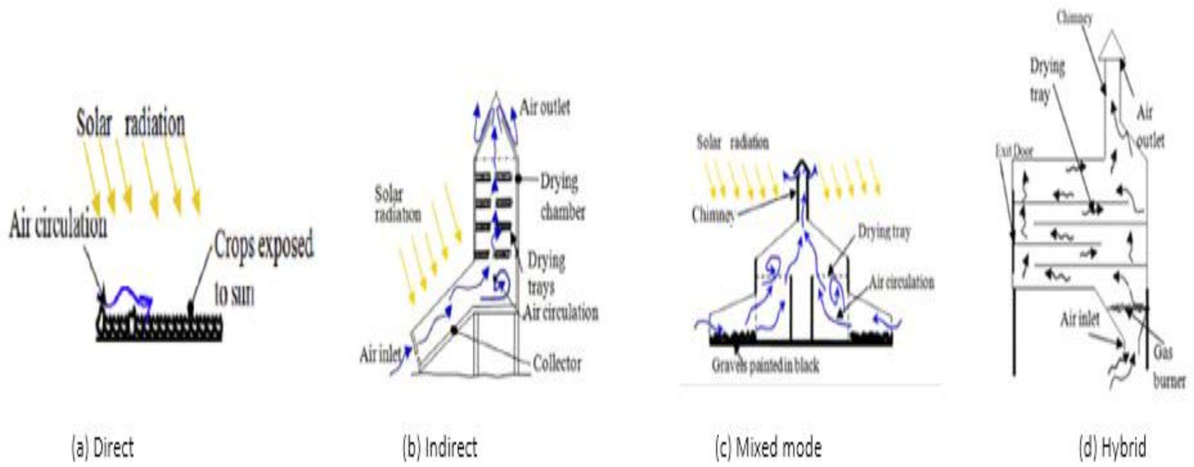
1- Direct solar dryer uses direct sun radiation to dry products. It is a simple design where the products are spreaded in a sunny place.

2- The indirect drying system uses an intermediate fluid which is heated by the sun radiation. The heat will transfer to the product by convection heat transfer method. The inside products do not receive direct sun radiation.

3- The mixed-mode drying system is a mixture of direct sun drying and indirect drying technique. The system is well benefited from the available solar radiation, so it recommended in low radiation cases.

4- Hybrid dryer uses at least two kinds of energy sources to dry the product like natural gas and solar for example.

Also, solar dryers grouped into active dryers where the auxiliary energy source is used for air circulation, a passive design where the air is following natural laws.



(a) Direct (b) Indirect (c) Mixed mode (d) Hybrid

**Figure 1 Solar drying systems [4]**

# 2.3 Solar Dryer with Built-in Storage

## 2.3.1 Indirect solar dryer

There are many designs in the literature for indirect solar dryers with thermal storage, they are grouped into a solar dryer system with closed-loop or without.

### 2.3.1.1 Indirect solar dryer with closed-loop

Vásquez et al. developed a solar dryer [7]. The design consists of three main components. A solar panel which is an absorber with perpendicular black zinc fins so the air inside the panel is heated by both conduction and convection. Thermal energy storage uses phase change material (PCM) which is Paraffin wax, it is filled in treated aluminum bottles to achieve high thermal conductivity. The drying chamber capacity was 25 kg with 10 trays and It is completely isolated to avoid direct solar radiation. In the daytime, incidence solar radiation is available, the air is heated inside the solar panel then it is introduced to the drying chamber. In the meantime, the solar radiation heats the air inside the paraffin wax storage for the charging purpose. The moist outlet air from the drying chamber exits through a vent valve. In the case of cloudy days, the air is heated by both the solar panel and the thermal storage. The air is used to remove the excess water inside kiwifruit and mushrooms. At night time, the air inlet and outlet are closed, the hot air in the storage flows to the drying chamber then it is circulated in the storage again to decrease its relative humidity so it can be used in the system again. Similar found is [8] for drying red chili.

Khouya et al. proposed a model [9] for an indirect solar dryer with built-in energy storage for drying wood as shown in Figure 2. The mass flow rate of the inlet air can be adjusted according to the desired drying rate and the available solar radiation. The model has four subsystems. Solar collectors to raise the temperature of the ambient air. Then the hot air will be transferred to the attached drying unit where the wood pieces are placed. When the air gets statured, it will leave the drying chamber to be heated again. After the sunset, the latent heat storage which was charged during sunshine hours It will be the responsible for heating the air.

Khouya et al. suggested a geometrical design for the energy storage unit. It is a hollow cylinder passes inside a container full of PCM. the charging of the storage is done using the irradiance concentrated by a parabolic collector. The hot air will pass through the hollow cylinder, and it will convert PCM from the liquid state to the solid-state. The parabolic solar concentrators in the proposed model can provide the average needed energy to dry the wood, and It is more economical if it compared to fossil fuel alternatives. Using solar energy made the system environmentally friendly like the design demonstrated in [10] [11].

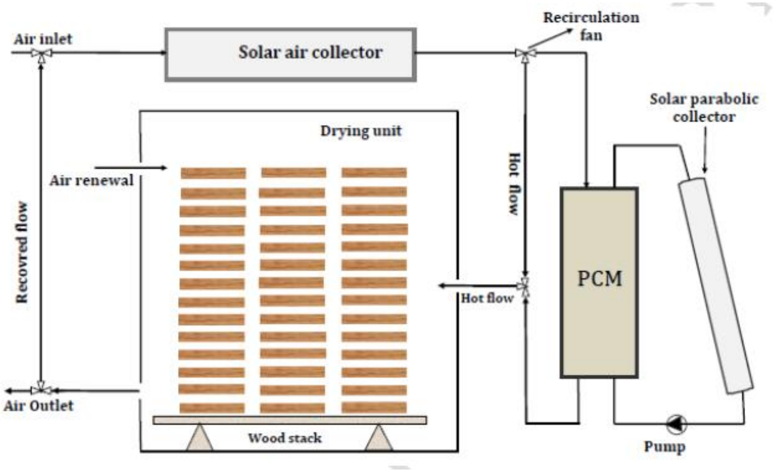


**Figure 2 The schematic diagram for solar dryer (Khouya & Draoui, 2018)**

Misha et al. designed and manufactured an industrial solar drying system for oil palm fronds [12]. A desiccant bed was used beside the conventional solar dryer components. Moreover, the system has two closed loops, one for the air and the other for water. The system takes the ambient air then dehumidified by the desiccant bed.  Then the air is heated up using both direct solar radiation and water heat exchanger. After that an axial fan pushes the hot air to the drying chamber. The wet air from the process will be passed through another water heat exchanger to raise its temperature, and this will consequently decrease its relative humidity. The relatively dry air is used to regenerate the desiccant wheel. The hot water used in both heat exchangers is heated using solar collector. An electric heater is used to heat the air at the nocturnal period, so the drying system works the whole day. Also, there is a hot water storage tank in the drying system design. The proposed prototype has a big capacity of 155 kg and  its efficiency is better than direct sun dryer efficiency . The same design was tested for kenaf cone fiber by the same author in 2015 [13].

Another study introduced an indirect solar dryer with integrated calcium chloride material to serve as a liquid desiccant for drying tomatoes [14]. The system was composed mainly of solar air collector, drying chamber, desiccant material tank, PV panel.  The working strategy is, the wet air from the drying chamber is passing through the liquid desiccant tank to reduce its relative humidity.  After that, it is pushed by the blower again to the solar collector entry to be warmed up and reused.  Calcium chloride is regenerated by passing over PV panels until the desiccant material concentration is equaled 30 % by mass. The drying system had an additional electric heater that can get its power from the PV panel.

### 2.3.1.2 Indirect solar dryer without closed loop

Jain et al. developed a model [15] for passive solar drying system with built-in storage in which all the drying components are combined in one device as shown in Figure 3. The system has two solar collectors, one inclined 25° degrees from the ground and the other is located above the drying chamber with 23° degrees' inclination angle. The packed bed number one is located under the drying chamber and the second follows the second solar collector inclination. For better efficiency, a mirror is used to reflect solar radiation on solar collector number one. The process described as, the air will flow from outside to solar collector number one, the energy captured from the sun will transfer to air. Then the hot air will be introduced to the drying chamber and thermal storage in the same time to charge it. Under buoyancy force, the moist air will go up and exit the dryer from the vent space between solar collector number two and thermal storage number two. At night, the air inlet and outlet will be closed, and the storage will start discharging, it will support the drying process for some hours and stop any micro bacteria development. The system was manufactured and tested for 60 -72 kg of leafy herbs and an economic study for the design done too. Quite similar designs in [16] [17].

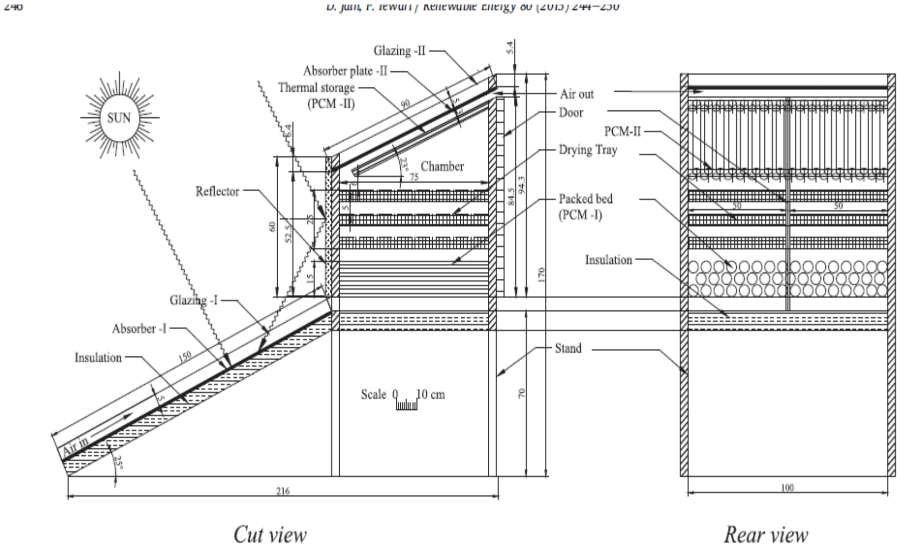


**Figure 3 The proposed solar dry model (Jain & Tewari, 2015)**

Thoruwa et al. fabricated solar dryer with desiccant material based as a packed bed [18]. The system was composed of a solar air collector connected to the drying unit which has the packed bed. The bed is located above the drying chamber and it is desiccant material / bentonite /calcium chloride material. The regeneration of the desiccant material is done by solar radiation through a layer of transparent insulation material placed on the top of the packed bed.  A fan was mounted inside the drying unit and it was connected to a PV panel/ battery system. In the morning, the air passes through the solar collector then it flows to the maize trays, the moist air exits system under natural, conventional force.  At night, no air is entering or exiting the system, and the fan will be put on to circulate air inside the drying unit. The advantage of using the desiccant material, it will not only work as a heat source but also it will absorb water vapor from the air so the air will be able to drag the moisture from maize. The experiment results have shown that maize can lose 18% of its moisture content in 24 hours.

### 2.3.2 Mix mode solar dryer

Abubaker et al. developed a passive mixed-mode solar dryer system with sensible heat storage in Nigeria [19]. The installed system was a solar collector connected to the drying chamber using three air ducts. The chamber has three trays, and each tray has its own chimney. The storage material used was gravel, and it was placed under a solar collector. The drying unit was fabricated from glass to allow solar radiation.  During sunshine hours, the hot air produced in the solar collector will enter the drying chamber through the separated ducts, this is to ensure that all the trays will have an equal chance to receive hot, dry air regardless the tray order in the chamber. The problem with the other designs, hot air is flowed for down trays to up ones so only the first tray will receive dry hot air, but starting from the second it will receive slightly moist air so the drying time required to dry yam will differ according to the tray position.  To avoid air flow interaction, the exhausted air from each tray will exit the system using a specific chimney, so each tray is entirely independent of the others. This design is optimal for large drying chamber which has numerous trays. During the night, no air will enter or leave the system. The gravel will release its energy which was captured from solar radiation in the morning to continue the drying process.

Another study designed a powerful mixed-mode solar dryer with a fan-operated by PV panel and battery [20]. The built-in energy storage was granulated paraffin, which is considered as latent heat storage. The system consists mainly of collector, energy storage, drying unit and fan. A new design for the solar collector was suggested where the distance between the flat absorber and glass insulation layer was divided into three parallel inclined ducts. Such design increased the collected energy from the sun. The drying process in the morning uses both convection and conduction heat transfer. Solar radiation energy transferred to the air inside the collector. Also, the apricot inside the dryer chamber will receive solar radiation since the top and the sides of the room made of plexi glass. The fan forces the saturated air to leave the drying chamber. The process at the night time, it depends on the storage which will heat the inside air. The results showed that the drying time for the dryer with storage was half the drying time for the dryer without storage, which means it worthy of having energy storage.

Lakshmi et al. made a comparison between forced convection mixed mode dryer with storage and an open sun drying system for drying black turmeric [21]. The mixed mode dryer used in the experiment had a unique design for a couple of reasons. The first reason, the collector has vertical fins which will increase the heat transferred by conduction. The second reason, the drying chamber shape is not the conventional cuboid, but it has divergent curves to increase the entry air velocity. The thermal storage was paraffin wax, and it had been integrated to help the operation at night, according to the results mixed mode dryer was faster than sun drying.

### 2.3.3 Greenhouse solar dryer

karunaraja et al. Studied the dryer performance using three different sensible thermal storages, sand, rock, and aluminum filings [22]. The dryer was a greenhouse design which is a tunnel with a transparent polyethylene cover. The system uses a controller to control the air velocity inside the tunnel to ensure constant drying rate. Two products dried in the experiment Vitis vinifera, Momordica. The results show that using the aluminum filings, the difference between the maximum and the minimum relative humidity of the air in the tunnel was 20 % although it was just 10 % for the rock and 15 % for the sand in Momordica drying experiment. In the Vitis vinifera experiment, the performance of aluminum filings and rocks thermal storage were better than the sand. The initial moisture content of Vitis vinifera was 85 % and to reach a final moisture of 10 % a 28.5 hrs. was needed using the sand bed, 29 hrs. using aluminum filings and 33 hrs. using rock. In the Momordica drying experiment, the desired final moisture content was also 10 %, it achieved within 5 hours using sand, 6 hours using the rocks and seven hours using aluminum filings.

The last aspect in the comparison was the moisture removal rate; aluminum filings used 19 hours to remove 24 grams of water from Vitis vinifera, the sand bed removes 34 gm in 18 hrs and the rock removes 34 grams of water in 16 hrs only. In drying Momordica, the sand was the first to dry it and aluminum filings were the last. The sand bed was the most efficient storage in drying Vitis vinifera, and Momordica, and the least was the rocks storage.

### 2.3.4 Hybrid solar dryer

Tarigan suggested a hybrid solar dryer with biomass burner and thermal storage [23]. The system was designed for drying 200 kg of candlenuts in one day. The model was composed of solar collector, drying chamber, biomass burner, thermal storage. The solar collector was a zinc sheet painted black with a glass cover. It used to heat the air in high solar radiation case. The drying chamber has an inclined glass top to allow direct solar radiation and stop the rains accumulation. The chamber has double walls from zinc sheets with 4 cm distances between the internal and the external layer. Mineral woods used to reduce the heat losses. The number of the trays was four each of an area equals 1.189 $m^2$.

Biomass burner was designed with a volume of 0.375 $m^3$ for the biomass feeding. The storage material was bricks and the storage was located above the biomass burner. The bricks were organized in a way to store the heat from biomass combustion. The combustion process hot air flows in the inner space between the drying chamber walls and it escapes from the system through the chimney as any passive system. The system operates as a mixed-mode solar dryer in the daytime and the biomass is used at night or cloudy weather.

## 2.4 Thermal Energy Storage Technologies

Energy storage is critical in the case of solar energy because the sun is not available everytime to fulfill the demand. Storing solar energy is about converting it to another form of energy and store the new energy form. In this thesis, we are concerned about converting sun radiation to material internal energy. This internal energy is heat, which can be sensible or latent, thermochemical [24].

### 2.4.1 Sensible heat storage

In case of sensiblized storage, solar energy is used to increase the temperature of the storage material which may be in the solid-state or liquid state. The storage capacity depends on the physical characteristics of the storage material like specific heat capacity and surrounding climate conditions and it is given by equation 1

$$Q = \int evc \ dt = m \, C \ (T_f - T_i) \qquad (1)$$

In the literature, there is some materials were defined as sensible heat storage.

In the solid-state, concrete is the best, then rocks and finally brick according to the material specific heat. From the density point of view, the rock has a high density compared to concrete or brick. All of them have the same working temperature range of 20 °C under one atmospheric pressure [17]. Sensible heat storage liquids are polar and nonpolar, Polaris are water, isotunal, proponal, ethanol, butanol, isopentanol, octane. The working temperature range and the specific heat for liquid materials is greater than solid. The highest working temperature is 148 °C for isopentanol, and the lowest is 78 °C for ethanol. Water has the biggest specific heat which equals 4190 J/kg, and the second is isotunal with 3000 J/kg, the last is isopentanol with 2000 J/kg [17].

Nonpolar liquids are only caloriea HT43 and engine oil. There working temperature range is bigger than solid and polar liquid materials. caloriea oil working temperature range is between 12 to 260 °C and engine oil range is up to 160 °C. Both of them have almost the same density, but caloriea has high specific heat compared to engine oil.

Despite the sensible storage simplicity and reliability, the designers do not choose it before considering the required isolation material and its efficiency and cost. In general, it is the cheapest technology compared with others.

### 2.4.2 Latent heat storage

Latent heat storage is based on the material phase change from one state to another. The amount of energy to be stored is a function of the latent heat involved in the phase as shown in 2

$$Q = m\,\lambda \qquad (2)$$

Where m is the material mass. Phase change process is not isothermal but it occurs within a range of temperature and the sensible heat due to the range is negligible. The latent heat storage is high energy density compared to sensible heat storage.

The materials used in latent heat storage is called phase change materials (PCM). There are a lot of research done to identify these materials. They are classified to three groups organic, inorganic, and eutectic. Each group is branched to other subcategories. Organic materials can be paraffin compounds or non-paraffin compounds. Inorganic materials are salt hydrates or metallic. Eutectic are organic -organic or inorganic -inorganic or organic-inorganic. more materials mentioned in [25].

In general, latent heat storage material can store at least five times sensible storage material and It can reach14 times [26]. The volume needed to store 1 million KJ is 2.7 $m^3$ of inorganic phase change material, 6.6 $m^3$ from organic PCM but it is only 30 $m^3$ for rock and 16 $m^3$ from water at T =15 K [17]. The amount of material needed for a latent storage is less than the amount needed for sensible heat storage which means latent heat storage is less costly compared to sensible heat storage. However, the problem of both types is the energy losses to surroundings which limits the storage life span. also phase change needs a large volume, and it is difficult to be handled.

### 2.4.3 Thermochemical heat storage

It is the energy stored by breaking bonds between different materials through a revisable endothermic physico chemical phenomena. The reaction is reversible, so when the energy needed, the materials react again in an exothermic reaction. Thermochemical heat storage has three different states charging, storing, and discharging. While the storage charging, solid or liquid material splits into two components. Then they stored separately. The discharging is done by remixing them.

Thermochemical storage materials are classified into liquid absorption, solid adsorption, and chemisorption [24].

Under the liquid absorption category, the commonly used working pairs are $NH_3$/ $H_2O$, $CaCl_2$ /$H_2O$, LiCl/ $H_2O$. For solid adsorption, silica gel/water, zeolite/water, (AlPO)/ $H_2O$. Chemical absorption can be the coordination of ammonia like $BaCl_2$/$NH_3$, $CaCl_2$/ $NH_3$. Also, it could be through hydration reaction of salt hydrate, for example, $MgSO_4$/water, $MgCl_2$/water.

The characteristics must be known before choosing the optimal material for certain application are material reversibility, corrosiveness [24], reaction temperature, reaction rate, and finally manufacturing ability. Thermochemical storage offers a high energy density compared to sensible and latent storage. Thermochemical materials can store energy in the ambient temperature so no temperature difference and no heat losses. The problem with thermochemical material is the cyclability and material degradation with time [26] .

## 2.5 Sorption Materials

In the previous section, three technologies were mentioned for storing energy. It seems that thermochemical is more suitable for our particular application and it is justified in section 3.3.3. The adsorption process is forming a layer from the adsorbate on the porous surface of the solid adsorbent while absorption process involves a liquid sorbent. The difference between adsorption and absorption is, the absorption process characterized by low output heat power and low-temperature drop during the discharging. however, adsorption has high output heat power[24]. In literature, there are many researches were conducted in sorption materials [27]. The common adsorption materials are represented as follows.

### 2.5.1 Silica gel

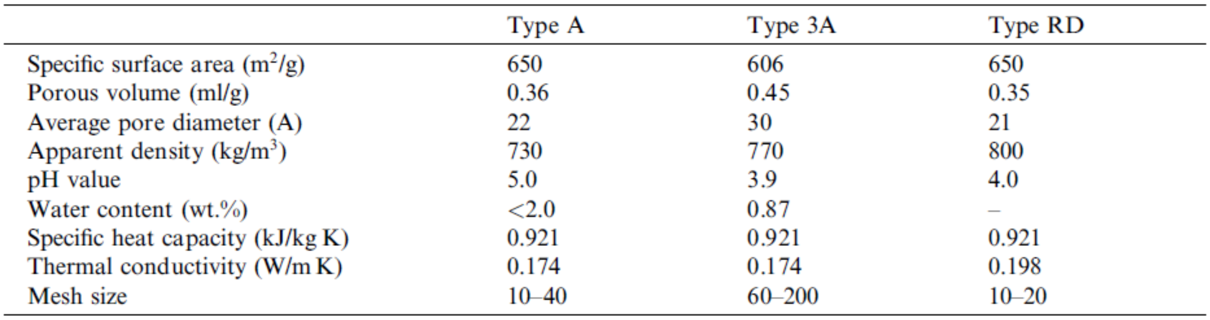
Silica gel ($SiO_2n\ H_2O$) is a chemical compound that consists of silicon dioxide and water. It is amorphous material, and it has a high ability to absorb the moisture from the surrounding. The absorbed water starts from 2.5 % to 40 % of the whole mass of the silica gel. The amount of water absorbed depends on the surrounding conditions, temperature, and pressure [28].

Usually, studies are conducted to determine the adsorption kinetics of silica gel, here an experiment done on silica gel type called Type RD. The maximum amount of water uptake was 300 g/kg, and it required 50 sec for the silica gel to get saturated at temperature equals 303 K and pressure of 2.26 kPa. It is known that the porous volume is directly proportional to the rate of adsorption and silica gel types with large porous volume have high process rate. After the experimentally and numerically investigation, there is no relationship between pore diameter and rate of adsorption. More, the experiment concluded that the regeneration rate is slow if the used silica gel is thicker and vice versa, the silica gel totally adsorbs the water after 800 secs in the case of silica gel with 1 mm thickness, 200 sec was sufficient when the silica gel thickness was 0.5 mm, with silica gel thickness 0.3 mm the time was reduced to 150 sec. For better performance silica gel often doped with another material like carbon, the result is high thermal conductivity type of silica gel [29] [30].

### 2.5.2 Silica gel types

There are many types of silica gel, here a comparison between three types Type A, Type 3A, Type RD as shown in Table 1 [31].

**Table 1 The different types of Silica gel**



| | Type A | Type 3A | Type RD |
|---|---|---|---|
| Specific surface area ($m^2/g$) | 650 | 606 | 650 |
| Porous volume (ml/g) | 0.36 | 0.45 | 0.35 |
| Average pore diameter (A) | 22 | 30 | 21 |
| Apparent density ($kg/m^3$) | 730 | 770 | 800 |
| pH value | 5.0 | 3.9 | 4.0 |
| Water content (wt.%) | <2.0 | 0.87 | – |
| Specific heat capacity (kJ/kg K) | 0.921 | 0.921 | 0.921 |
| Thermal conductivity (W/m K) | 0.174 | 0.174 | 0.198 |
| Mesh size | 10–40 | 60–200 | 10–20 |

It is very important to know the isotherm characteristics of the silica gel type before choosing it for specific application. Isotherm characteristics are always represented by Henry law it is a function between q* the amount of water adsorbed to the adsorbent mass, $Q_{st}$ isosteric heat of adsorption, the surrounding air temperature and pressure.

$$q^* = k_o{}^1 \exp[\frac{Q_{st}}{R\,T}]\ P \qquad (3)$$

where $k_o{}^1$ is 5.2 E-12 $pa^{-1}$ for Type 3A, 5.5 E-12 $pa^{-1}$ for Type RD. $Q_{st}$ is 2380 KJ/kg for Type 3A, 2370 KJ/kg for Type RD.

Silica gel regeneration or adsorption process is a function of temperature and time. In general, silica gel regenerated at low temperature, in the experiment, the three types started the adsorption process at 40 °C, and they finished at 90 °C. Type 3A desorbs 40 % of the inside moisture at 40 °C, while only 20 % was desorbed by Types A, CD at the same temperature as shown in Figure 4. To determine the time needed for the regeneration hot air at 140 °C was used, it takes only 2.4 minutes for Type 3A to be regenerated, 4 min for Type RD and 5 min for Type A [31].

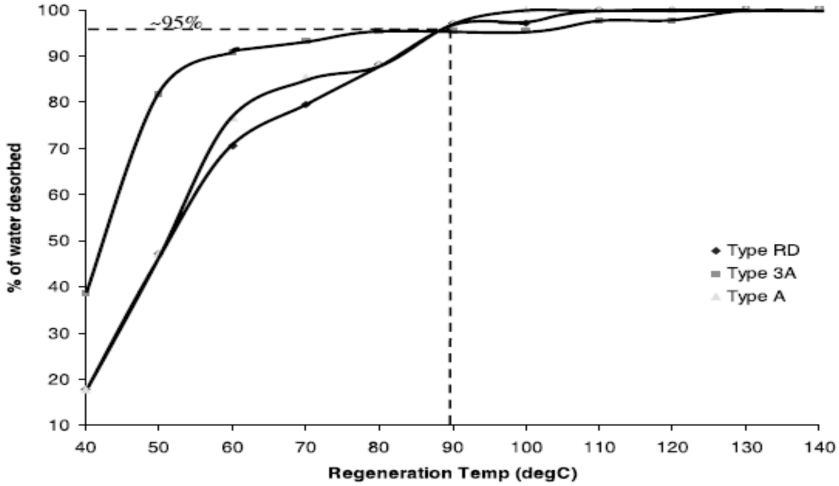


**Figure 4 The percentage of desorption at various temperature (K.C. Ng, H.T. Chua , C.Y. Chung, C.H. Loke, T. Kashiwagi, A. Akisawa, 2001)**

### 2.5.3 Zeolite

It is a chemical compound composed of $SiO_4$ bonded to $AlO_4$. It can be hydrophilic or hydrophobic depending on which is the dominant aluminum molecules or silicon molecules, and also the crystalline structure. The perfect ratio for Si /Al in the compound is 8 to 10. In the zeolite, the pore diameter affects the amount of water uptake. Also It has high storage capacity conversely it is difficult to be regenerated. There are many types of zeolite, like 5A,13X, 13X/$CaCl_2$ [24].

Sayilgan et la. studied Zeolite 13x/ water as adsorbent /adsorbate [32]. The particles of the used Zeolite 13X had a diameter 2.38- 4.76 mm. The zeolite ability to adsorb the humidity decreased with increasing the temperature at constant pressure. The zeolite adsorbed 23 % of the water at 35 °C and was reduced to 19 % at 60 °C both experiments were done at pressure 1500 Pa. For the regeneration temperature and the adsorption capacity, the experiments showed that increasing the temperature increase the amount of water adsorbed. Zeolite released 22 % of the whole water at 90 °C, and by increasing the temperature to 150 °C it released 24 % at 1000 Pa.

### 2.5.4 Comparison between Silica gel types and Zeolite types

Further, comparing the behavior of silica types and zeolite types will lead to a better understanding of which one is more suitable for a particular application. Li et al. in 2014 compared six silica gel types (silica gel B, silica gel 3A, silica gel RD, silica gel/LiCl, silica gel/$CaCl_2$) with three zeolites (zeolite 5A, zeolite13x, zeolite13x/$CaCl_2$) and another sorption material (LiCl, $CaCl_2$).

The study introduced some indices for the comparison,

1- The specific dehumidification power SDF (g /Kg h) which is the power needed for the regeneration of a section to the power needed to regenerate the whole cycle.

2- The dehumidification efficiency $\varepsilon_p$ which is the difference between the inlet and the measured humidity ratio to the difference between the inlet and ideal humidity ratio.

3- The dehumidification coefficient of performance COP, which is the energy consumed in the adsorption process to the useful energy needed for the process.

The results show that SDF is directly proportional to the temperature, the silica gel types 3A, RD, B adsorbed approximately 700 g/kg h at 60 °C. On the other hand, zeolite 5A and zeolite 13X released around 500 g/kg h, and LiCl and $CaCl_2$ only released 100 g/kg h at the same temperature. Form the dehumidification efficiency point of view, all silica types gel had an efficiency between 40 % - 45 %, however, all the other types had 22.5 % - 25% at 80 °C as shown in Figure 5 . The last index was the dehumidification coefficient of performance. Two groups were found, the first group contains zeolite 5A, zeolite13X, zeolite13X/$CaCl_2$, LiCl and $CaCl_2$ where COP was less than 0.6. The other group was the silica gel types which have COP greater than 0.6 [33].

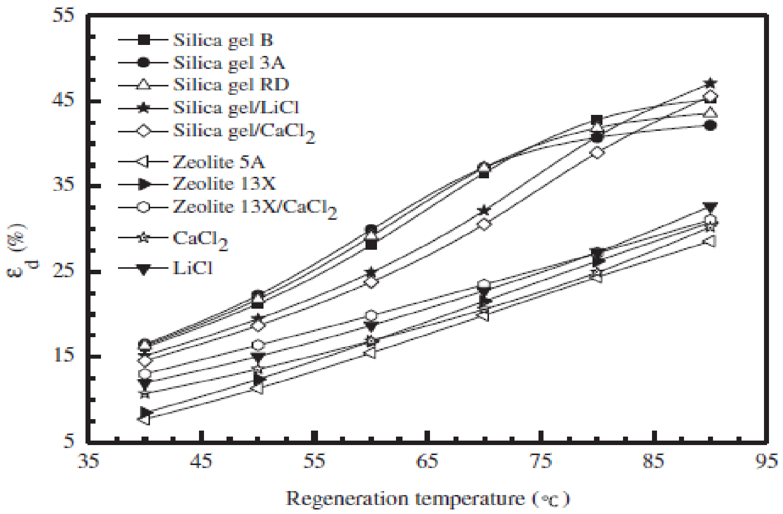


**Figure 5 Dehumidification efficiency at hot humid air (Zhang, Fu, Yang, & Xu, 2014).**

## 2.6 Solar Dryer Used Within the African Continent

Form the literature we get to know some trials in this field aside from the mixed mode model designed in Nigeria [19],

A hybrid solar drying system designed in Algeria [34], it was used for drying tomato in the winter season. The system depends on the solar radiation to heat the air, but if the radiation is not enough. There is an electric heater placed inside the drying chamber. The porotype has a temperature controller which measures the temperature of the air entering the drying chamber, and if it is less than the programmed value, the controller will give a signal to turn on the electric heater. The drying system had a fan which placed on the bottom of the chamber.

Boroze et al. conducted a survey in Burkina Faso and two other West African countries Togo, Benin [4]. The different types of solar drying systems used in the survey region was summarized. The authors first notice was that the majority uses direct sun drying systems like spreading on plastic sheet, tent design, direct cupboard structure because no capital cost is required for direct sun drying. Only two designs found for indirect solar dryers in the region. One named shell which is composed of two cones connected by a hinge. Some NGOs introduced it, but by the time problems start appearing, and people stopped using it. The second indirect dryer design was similar to [15] but without energy storage. The survey determined that only one design for the mixed solar dryer is used, which was simple and worked under natural convention. Also only one design for a hybrid gas /solar dryer is used in three countries. Based on the authors' analysis, the successful dryer designs are the gas dryers Atesta and maxicoq for massive production and direct solar dryer for the family-scale.

Another study proposed a design of indirect solar dryer with natural convention without energy storage for drying mangoes in north Sudan [35]. The article describes in detail the procedure to determine the required solar collector area, to calculate the optimum dimensions of the air inlet and outlet windows, and to design the drying chamber. A prototype for drying two kg was constructed, then experiments were conducted on it. The results show that using the proposed design only 20 h are needed to dry 195 kg of mangoes to a final moisture of 10% wet basis.

In Ethiopia, Demissie et al. developed and manufactured indirect solar dryer without packed bed [36] which can work as a passive dryer with a chimney or active dryer because there is attached fan. The authors tried to reduce the vapor condensation at the air outlet by designing it in the shape of a truncated pyramid. The design was also modeled using computational fluid dynamics (CFD) and validated by comparing the measured temperature inside the dryer to model output. The result was that the maximum difference between the recorded and the predicted temperature was 4.3 °C.

## 2.7 Solar Dryer Designed in Burkina Faso

In the past few years, some research was conducted in Burkina Faso to dry mangoes slices.
In 2009, Dissa tried to dry mangoes with indirect solar dryer. The dryer was passive with PVC chimney and without energy storage. The working principle was the ambient air will be heated up in the solar collector which was 1.7 $m^2$, then it will be dragged to the drying unit. The hot air will evaporate the water inside mangoes, and its relative humidity will increase, after some time it will be exhausted, and following thermodynamics laws, it will exit the system. The results were not a good, especially in the terms of the required drying time; it was three days for 2 kg mangoes [37].

The same author in 2011 conducted the another experiment by using a direct solar dryer. The experiment design was that mangoes slices would not be on direct exposure to the radiation, but it will be partial because the slices were placed in four trays and only the first tray received the direct solar radiation. The dryer sides were covered with a nylon layer to avoid the unwanted interaction with the surrounding. The study aimed to determine the drying characteristics of different mangoes varieties under direct solar drying and Ouagadougou climate conditions. The result was that 4 days are required for the drying process of 1.4 kg mangoes and clearly shown that the tray position affects its drying rate [38] .

Desmorieux et al. suggested a semi-industrial drying system which can dry 500 kg of mangoes per-cycle [2]. The system consists of the gas burner which warms the air to 60 °C and 10 % relative humidity; then the air stabilized for some time before entering the drying tunnel which can be occupied by 12 wagons each had 21 trays. The wagons are not static inside the tunnel, but they are rotating against the air movement direction. The drying operation inside dryer simulated, and the results showed that all the mangoes achieved the desired moisture content at the same time. Furthermore, the drying time was one day and a half which means 12 h delay compared to the expected drying time, according to the authors is the problem was the high relative humidity of entry air.

# CHAPTER THREE: METHODOLGY

## 3.1 Burkina Faso

Burkina Faso is a West African landlocked country located between nine to fifteen north latitude and for longitude is between six west to three east. With an area equals 274000 km$^2$, a population of approximately 20 million. Almost 28% of citizens work in the agriculture sector [3] and It contributed 27.82 % of the GDP in 2017. Burkina is a low income with GDP per capita 670 $ in 2017, and only 25 % access to electricity [3]. More on, Burkina Faso is famous Four mangoes verities out ten produced in west Africa, the mangoes production in Burkina Faso is 154000 – 252000 t annually [1]. Some of the mangoes are exported fresh, dried, or as juice and the others consumed locally.

### 3.1.1 Climate conditions

Burkina has tropical climate conditions, and the year has two seasons the rainy from May up to September and the dry from October to April. The country has 3 zones as shown in Figure 6, the Sahel in the north, Sudan - Sahel in the middle and Sudan-Guinea in the south. The weather in Burkina Faso in general is humid air with temperature range from 28 °C to 41 °C, daily solar irradiance 140 -190 kWh/m$^2$ as an average [39].

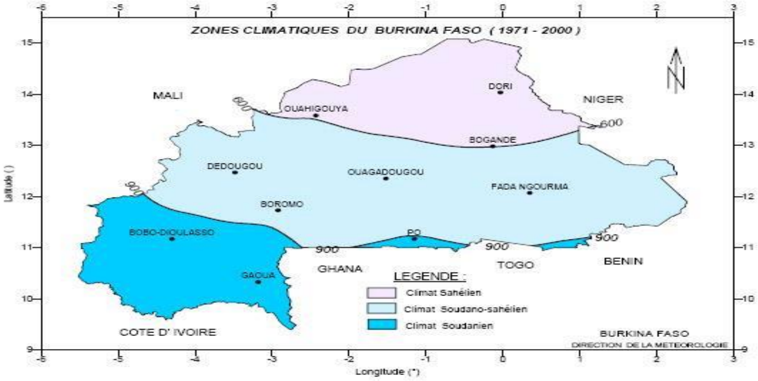


**Figure 6 The climate zones in Burkina (Diarra, Barbier, & Zongo, 2017)**

Mangoes production is concentrated in the south and especially in the province L'houet which has bobo-dioulasso city because the climate conditions there are suitable to plant mangoes. Bankandi village which is 187 km from bobo-dioulasso city, was chosen to be the case study for this work because it has ground weather station. The station related to research work is ongoing by WASCAL competence center in Ouagadougou [40]. The station coordinates X : 491623.78, Y :1243228.52. The average monthly temperature accorded in period 2012 - 2015 is shown in Figure 7.

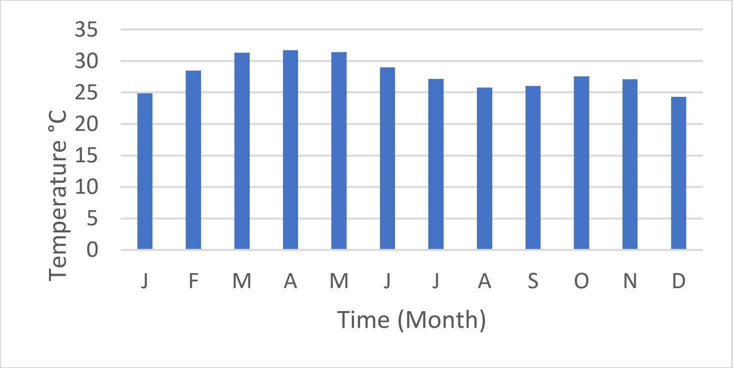


**Figure 7 The measured temperature range in Bankandi**

As mentioned above, Burkina Faso has moist weather. In the station, the relative humidity measured by Campbell's CS215 sensor in 1.5 m, the values above 100 % rounded to 100 %. Figure 8 shows the average monthly measured values over four years.

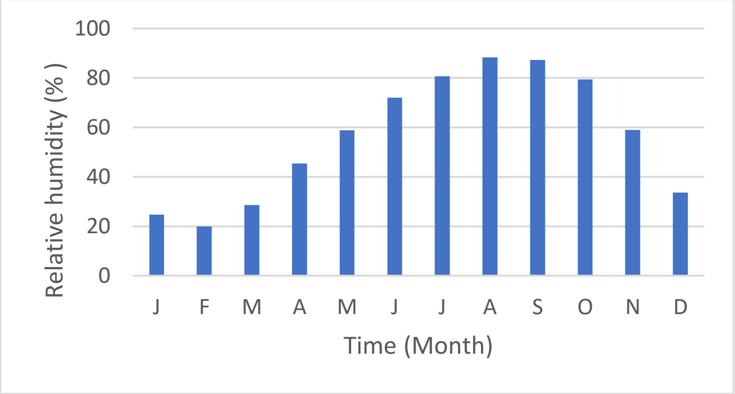


**Figure 8 The measured relative humidity range in Bankandi**

Burkina Faso has Harmattan wind which blows from the east to the west almost the whole year, the average monthly measured values are represented in Figure 9.

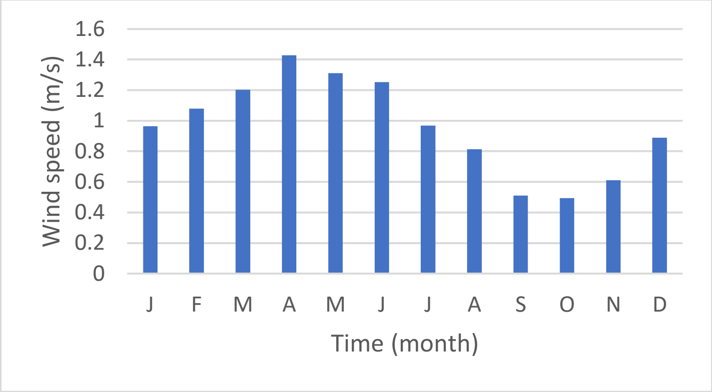


**Figure 9 The measured wind speed range in Bankandi**

### 3.1.2 Solar potential in Burkina Faso

Burkina Faso has vast solar energy potential, and the north region receives 6 kWh/m$^2$, and the south receives 5.4 kWh/m$^2$.  The minimum astronomical sunshine hours are 11 hours. The minimum sunshine hours are 7 hours all of the year.  Figure 10 represents the global solar irradiance in Burkina Faso [5].

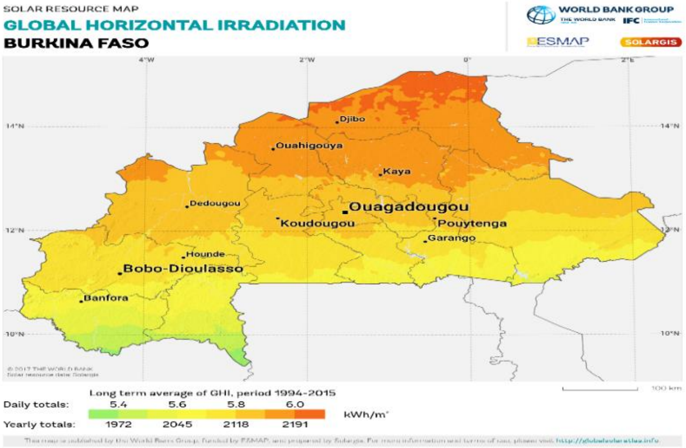


**Figure 10 Global horizontal irradiance  in Burkina Faso [5]**

The solar energy potential is high in Burkina Faso in general, the global horizontal irradiance received in Bankandi accurately recorded every 10 minutes, then the data were cleaned from the false measurements, negatives values were round to zero.  Figure 11 represents the measured solar radiation.

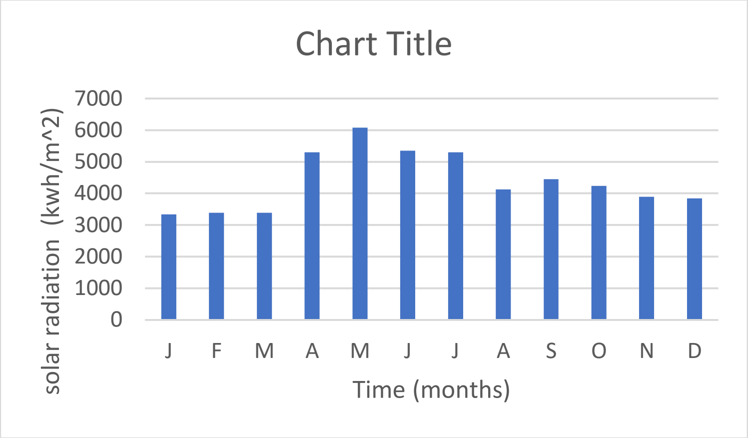


**Figure 11 The measured solar radiation range**

## 3.2 Mangoes as Dried Fruit

### 3.2.1 Different varieties

The mangoes production in the west African countries equals 1.4 million t annually [1]. There are ten varieties of mangoes cultivated in the region. In Burkina Faso, four varieties are available Amelie, Brooks, Kent and lippens [1].

Due to limited local studies, the comparison is between Amelie and Brooks varieties. The Amelie acidity range is between 5.8 -12 mmol /100 g pulp, and it is higher than Brooks, which is 7.51-5.69 mmol /100 g pulp [38]. For the sugar content, Brooks are less sweetie compare to Amelie. The range is 9.3 -13.5 °Brix for Brooks and 12.3 -15.7 °Brix for Amelie. The initial moisture content in both varieties is high, 600% on the dry basis for Amelie and 582 % on the dry basis for Brooks. To get stable mangoes after the drying process, the final moisture content for Amelie should be between 15 -20 % wet basis, which is almost half the desired final moisture for Brooks [38] .

In the direct sun drying experiment which were done on both Amelie and Brooks slices , Brooks slices lose more water than Amelie slices in the first drying day; however, Amelie slices dried faster than Brooks slices at the end of the experiment [38]. Moreover, the drying rate of Amelie slices was a little bit higher than Brooks slices drying rate. The diffusivity was high for Amelie slices on the first day compared to Brooks slices, but in the second drying day, Brooks slices were better than Amelie slices, in the third and the fourth days Amelie slices keeps heading Brooks slices. For the process efficiency, it used to be high then to fall for both varieties. The maximum efficiency for Amelie was 34.4 %, but it was only 28 % for Brooks slices.

### 3.2.2 Amelie is the chosen variety

Amelie mangoes are chosen to be the working variety for the proposed solar drying system. There are many reasons for choosing Amelie as following.

Amelie mango harvesting season starts in April and ends in June. However, for Brooks variety, it is from June to August. After studying the local weather, the minimum temperature in the Amelie harvesting season is 29 °C, but it goes to 26 °C in Brooks harvesting season. Although during both Amelie and Brooks season, the air is humid. But in Amelie season the average relative humidity equals 72 %, and it equals 88 % on Brooks season. So the weather conditions in Amelie is a bit less challenging compared to Brooks case.

There are studies for Amelie mangoes characteristics in the drying process [41] ; consequently, there are enough data about water diffusion inside the mangoes slices, the expected slice shrinking after drying at a certain temperature, the effect of the air temperature and slice thickness on drying kinetics and the process rate. Such studies result on the maximum temperature which the slices can be dried on, the equilibrium moisture content for the dried mangoes. For Brooks mangoes, there is no such information, untimely involving it a drying process.

## 3.3 System Design

### 3.3.1 Proposed design

The proposed system is an indirect solar dryer with dehumidifier unit and built-in thermal storage, the designing parameters are summarized in Table 2 .

**Table 2 Design assumptions**

| Item | Assumptions |
|---|---|
| Location | Bankandi village (latitude :11.2 °N) |
| Crop | Mango |
| Variety | Amelie |

| | |
|---|---|
| The harvesting season | April – June |
| Capacity of the dryer | 100 Kg |
| Moisture Content at harvest | 85 w.b % |
| Moisture Content for storage | 15 w.b % |
| Maximum allowable temperature | 60 °C |
| Inlet temperature of the drying chamber | 60 °C |
| Average temperature | 30 °C |
| Average relative humidity | 72 % |
| Sunshine hours | 12 h |
| Average solar radiation | 5 kw/m2 |
| Maximum drying time | 24 h |
| Collector efficiency | 30 % |

The drying system is composed mainly of four parts, which are solar air collector, dehumidifier unit, drying chamber and thermal energy storage. The parts are assembled in one structure similar to indirect cupboard design, as shown in Figure 12 . The dehumidifier based on sorption material which is placed in the distance between the black absorber plate and the glass. The solar collector has some fins to increase the thermal conductivity. Double wall is used to isolate the drying chamber and to decease thermal losses. The thermal storage is located above the drying chamber and it is facing the sun. The suggested solar dryer uses forced convection. A fan pushes the air in multiple ducts to enter the drying chamber in the morning and it used to circulate the inside air at night.

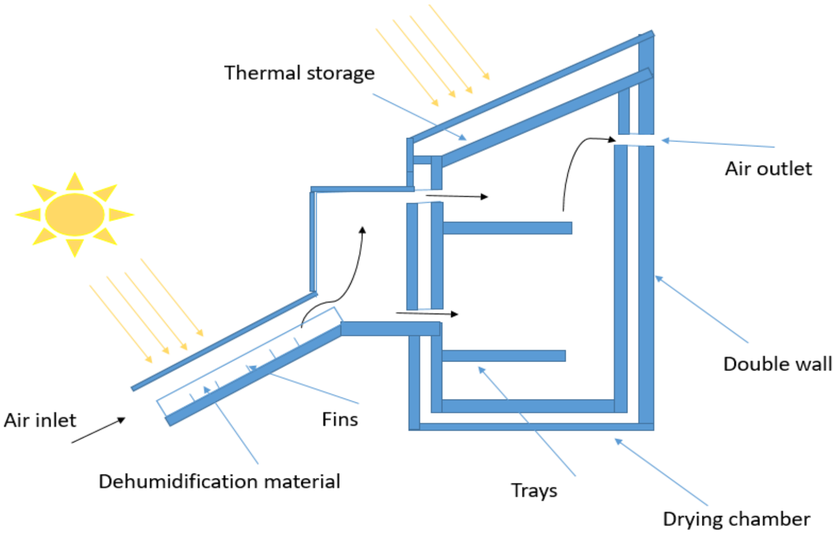


**Figure 12 The proposed indirect solar dryer model**

The working strategy at the daytime is, the ambient air passes through the dehumidifier unit to decrease its relative humidity, the air is heated up inside the solar air collector. The dry and hot air is flowed through the different ducts which each connected to a tray. The saturated air will leave the drying chamber through an output window. A schematic diagram shows the strategy in Figure 13 .

At the night time, the air inlet and outlet will be closed, the thermal storage will heat the air in the drying chamber, and it will reduce its moisture content because the storage material has adsorptive characteristic. Such air will face the mangoes and extracts the undesired water content. Then the air will be humid, and the desiccant material will absorb its humidity again. This process will continue until the storage material will be saturated with the free water inside the mangoes. Before starting drying the mangoes, they have to be weighted, then during the drying process, the slices will be reweighted regular to determine when the process will be finished.

The regeneration of the sorption material in the thermal storage will be done in the morning using the solar radiation. For the dehumidification unit, two beds of sorption material will be used, so one will be regenerated while the second in connected to the system. The saturated will wait to the following morning the regeneration. The change of the sorption material beds will be done manually.

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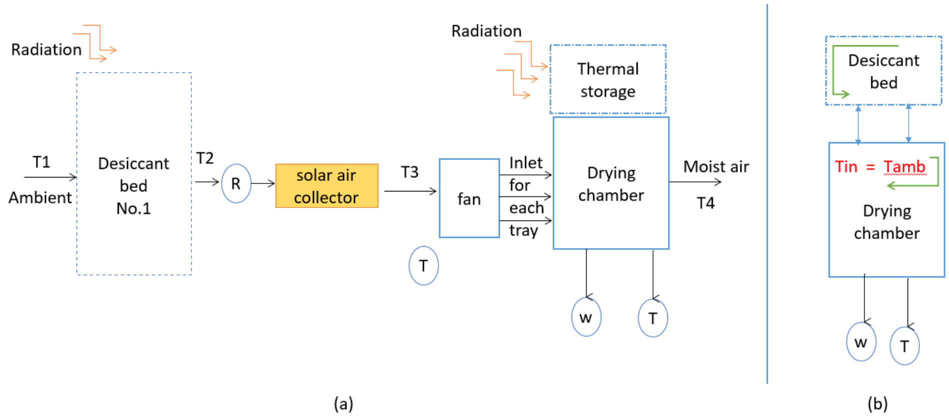

(a) (b)

**Figure 13(a) The working system in the day time and (b) in the night time**

There are three processes are done in the purposed system. The dehumidification process which is modeled as an isothermal process, the silica gel desorbs the moisture in the air at a constant temperature. The air then will be heated in a sensible heating process in which the absolute humidity ratio is constant, but the air relative humidity and temperature are variables. The drying process in the chamber is modeled as ideal adiabatic humidification, the process is assumed to be done at air temperature equals the air wet-bulb temperature. Figure 14 shows the processes representation in the psychometric chart.

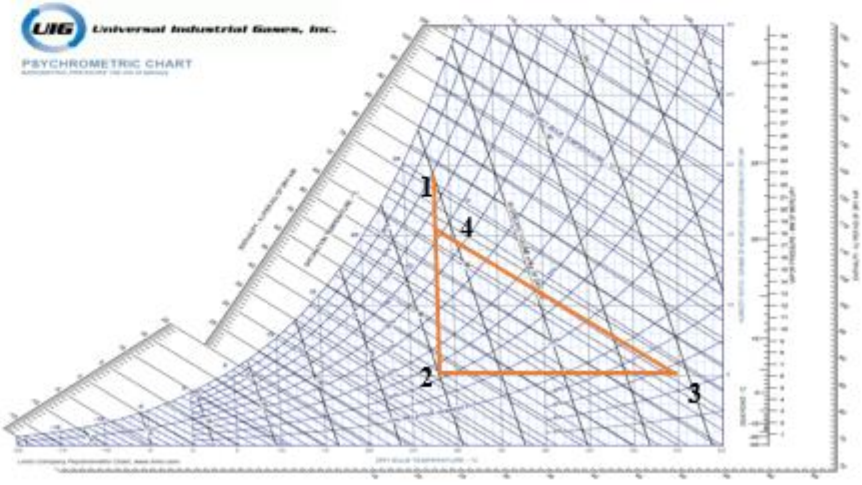

**Figure 14 The processes in the psychometric chart**

### 3.3.2 The justification for the chosen design

The indirect type is suggested to reduce the drying time. The required drying time for Amalie mangoes using direct solar radiation was four days in Dissa experiment [38]; however, only three days were enough using indirect dryer [37]. The indirect design was effective in terms of the amount of removed water each day.

However, both the indirect and direct solar dryer occupy almost the same area, but the indirect model has the advantage of ensuring equilibrium drying for all the mangoes without consideration of tray position or the mango location in the tray [37]. This point is very vital for the mass production of dried mangoes [38]. Also, many air ducts suggested in the design, each one connected to a tray in the drying chamber. The different ducts used will help to achieve equilibrium drying rate because each tray will receive hot dry air not only the first tray [19].

The sorption material in the dehumidifier will reduce the high relative humidity of the ambient air before introducing it to the drying chamber. because when the humid ambient air used in the drying process, it increased the drying time by 20 % [42]. According to [2], the drying time was expected to 24 hrs but because of the high moisture content of the air, the drying time was 36 hrs.

The silica gel was chosen for the dehumidifier because it has high water uptake at 40 °C which is within the drying process temperature. Silica gel can be regenerated in less than 90 °C but zeolite 13x needs 90 °C to 150 °C [42].

Type RD Silica gel selected among silica gel types because of its initial water uptake values. It was 40 % from the whole water for Type RD, but Type 3A was able to absorb only half of this value in the same 40 °C [31]. Both types absorbed the whole water at 90 °C, and they showed quite similar behavior in the adsorption regeneration cycle [31].

### 3.3.3 The justification for the chosen thermal storage

Sensible storage is characterized by the high energy losses, although latent storage can stand for one day, and it is better in terms of the losses [24] . Both technologies cannot emulate and cannot work in the local context because both of them need insulation which is costly. The rainy season in Burkina Faso has the lowest solar irradiance in the year, as shown in **Error! Reference source not found.**. So the desired storage should be able to fulfill the energy needs for some time for example three days with a moderate cost.

Also, mangoes are high water content fruit in which the desired final moisture content should be 15 % wet basis; however, the initial moisture is 85 % wet basis [38]. Considering that 500 kg should be dried daily, very high energy storage is required [2].

Consequently, the sizable storage must have a high energy density. The highest energy storage ability is the chemisorption and physisorption thermochemical storages. Both of them are not applicable or mutual until now because of the reaction after some time become irreversible [24]. Moreover, the operating temperature is too high for a simple solar application that will operate in the rainy season, and it starts from 200 °C to 1000 °C [24]. Also having storage depending on these technologies in acceptable cost is a challenge. Taking into account that the dryer manufacturing cost must not be too high so people can afford and do profitable business with accepted payback time.
The other dense storage is adsorption thermochemical storage, and it is the best to be used in the drying process in Burkina. Not only because of the high energy density and high heat power but also because of its operating temperature, it is less than 90 °C, and this threshold is achievable in the local context. Further, the weather characterized by high relative humidity as Figure 8, sorption energy storage will heat the air and absorb its moisture content. Having relatively dry air will enhance its tendency to absorb the moisture from mangoes.

There are many working pairs defined for thermochemical sorption storage to choose which one is optimal for our dryer regeneration aspect was considered. The regeneration usually is done by a wheel design, which is difficult to be manufactured and it required regular maintenance for the rotating parts [12]. In Burkina Faso as a country, maintenance service is not easy to be found, especially in the rural area where mangoes are planted [4] . Using the wheel design will require conducting training for the users, which will be a costly activity and not practical on the long run. The choice goes for silica gel/water as a material because it can be regenerated using solar radiation likes Harare Zimbabwe experiment [43].

### 3.3.2 A dehumidifier unit

The ambient air has high relative humidity between as shown Figure 8. Using such air in the drying process will decrease the drying rate, it will increase required time to achieved the desired product and this can lead to bacteria development in the mangoes [2]. Dehumidifier unit will take the air from outside and it decreases its relative humidity using isothermal process. The output air will have low relative humidity so it will have high ability to absorb the moisture inside the mangoes compared to the ambient air.

air dehumidifier designing tool is one of the three tools proposed in this study; The dehumidifier design tool will able to calculate the amount of material needed to absorb all the humidity of the air in the morning working hours. The working strategy is represented in the flowchart Figure 15.

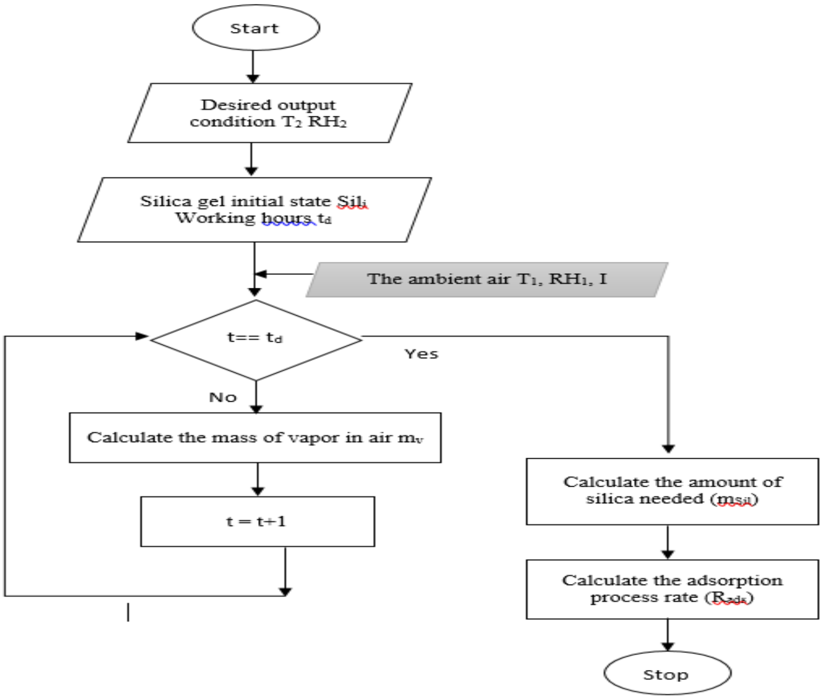

**Figure 15 the de humidifier design tool flow chart**

Assuming that the sorption process is isothermal, the temperature of the output air from dehumidifier $T_2$ equals ambient air temperature $T_1$.

The amount of water vapor to be removed from the air equals $m_v$ [35]

$$m_v = (X_1 - X_2)\ ma\ (t_d) \qquad (4)$$

Where $X_1$, $X_2$ are the absolute humidity of the ambient and the dehumidifier output air (kg $H_2O$ /kg dry air). The absolute humidity of the air $X_1$ (kg $H_2O$ /kg dry air) calculated as [44]

$$X_1 = 0.62198\ \frac{P_{sat}}{P_1 - P_{sat}} \qquad (5)$$

Where $P_{sat}$ is the saturation pressure at final product temperature and it calculated as [44]

$$P_{sat} = \exp\left(\frac{C_1}{T_1} + C_2 + C_3\, T_1 + C_4\, T_1{}^2 + C_5\, T_1{}^3 + C_6\, \text{In}T_1\right) \qquad (6)$$

Where $C_1$ = - 5.8002206 E 3, $C_2$ = 1.3914993 E 0, $C_3$ = - 4.8640239 E-2, $C_4$ = 4.1764768 E-5, $C_5$ = 1.4452093 E-8 and $C_6$ = 6.5459673 E 0. The measured pressure $P_4$ is

$$P_1 = P_{sat}\, RH_1 \qquad (7)$$

For $X_2 = X_3$ because the heating process inside the solar air collector done at constant absolute humidity.

The initial moisture content inside the silica gel $Sil_i$ is 2.5 % of its mass. The saturation moisture content of silica gel $Sil_s$ equals [43]

$$Sil_s = 0.6114\ (RH_2)^{1.2646} \qquad (8)$$

Where $RH_2$ is the relative humidity of the dehumidifier output, it calculated from $T_2$, $X_2$.

The mass of the silica gel needed for dehumidifier $m_{sil}$ equals

$$m_{sil} = \frac{X_1 - X_2}{Sil_s - Sil_i} \qquad (9)$$

The rate of adsorption $R_{ads}$ (kg/hr) equals the difference in the absolute humidity of the inlet and the outlet air multiplied by the mass flowrate of the air (kg/hr) [42]

$$R_{ads} = m_a(X_2 - X_1) \tag{10}$$

### 3.3.5 Solar air collector

The drying chamber connected to air solar collector which heats the air. Then the fan pushes the hot air inside the chamber. The solar collector design tool takes the drying capability, the mangoes initial moisture content, the desired final moisture content for the mangoes, number of sunshine hours, received radiation and the ambient air conditions. The tool will calculate the solar collector required surface area, the required air mass flow rate and the energy needed for the drying process. The code flow chart as shown Figure 16.

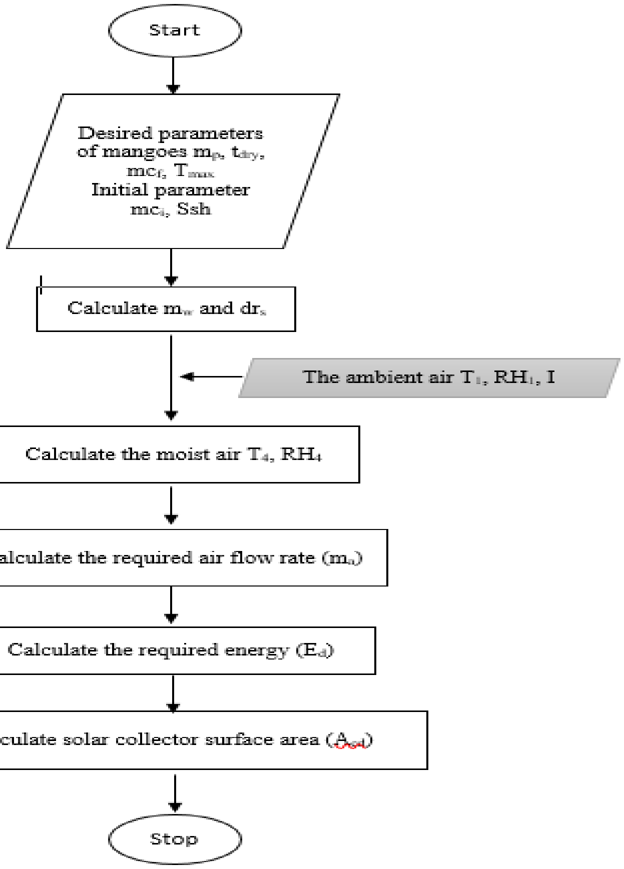

**Figure 16 The solar collector design tool flow chart**

The required solar collector area depends mainly on dryer capacity, which is the amount of mango to be dried. According to [2], the dried mango producers had a bulk of 500 kg sliced mangoes, and it had to be dried every day. Considering that the stone had been removed firstly, the mango pulp cut in slices, then the mangoes weight will be $m_p$. The excess water inside the mangoes mw calculated as [35]

$$m_w = m_p \frac{(mc_i - mc_f)}{100 - mc_f} \tag{11}$$

Where $mc_i$, $mc_f$ is the mangoes initial and desired final moisture content in wet basis. The excess water is divided into two types of surface water, linked water. Surface water shear $S_{sh}$ is approximately 18 % of total excess water weight, and the linked water represents the rest. During the drying process, surface water will be separated first because it is easy to be evaporated, but the linked water will take more time [45] .

The drying process rate for surface water $dr_s$ which will be done at the nighttime, it calculated as [35]

$$dr_S = \frac{m_w \ X \ S_{sh}}{t_n} \tag{12}$$

where $t_n$ is the night time because the stored energy is not significant compared to solar energy, The linked water will be removed in the daytime, the drying rate $dr_L$ calculated

$$dr_L = \frac{m_w \ X \ (1 - S_{sh})}{t_d} \tag{13}$$

where $t_d$ steads for the daytime [35].

The correlation of Amalie mangoes equilibrium relative humidity $RH_4$ was determined in [37]

$$RH_4 = 1 - \exp({m_f}^{0.3316} \ x - 0.0193 \ x \ [T_4 + 44.36]\,) \tag{14}$$

Where $T_4$ is the final product temperature. $T_3$ equals $T_{max}$ which is a result of Amalie mangoes drying characteristics study [38].

The mass flow rate of the air needed for drying in the morning [35]

$$\dot{m}_a = \frac{dr_s}{X_4 - X_2} \qquad (15)$$

where $X_2$ , $X_4$ is the absolute humidity of the air entering the solar collector and the output from the drying chamber.

The amount of energy needed for drying in the daytime $E_d$ (J) equals to [35]

$$E_d = \dot{m}_a (h_4 - h_2)\, t_d \qquad (16)$$

Where $h_4$, $h_2$ the enthalpy of the initial state of the air and the final state in (J/kg).

The area of the air collector $A_{cd}$ ($m^2$) required for the drying process in the morning is [35]

$$A_{cd} = \frac{E_d}{\eta I} \qquad (17)$$

Considering the collector efficiency η is 30 % or 50 %, I is the total global radiation on the horizontal surface ($J/m^2$).

### 3.3.6 Thermal energy storage design

The thermal storage designed to provide the drying system energy needs at the night time. The storage has to heat the inside air so it absorbs the free water in the mangoes. When the air will get saturated the sorption material has to absorb air moisture content so it becomes dry again.

The storage design tool takes the dryer capacity, the mangoes initial moisture content and the desired final moisture content for mangoes. The tool will be calculated the amount of water to be removed, the amount of material needed to absorb this water, the time needed for the regeneration process of the sorption material and the rate of the process. The tool flowchart is shown Figure 17.

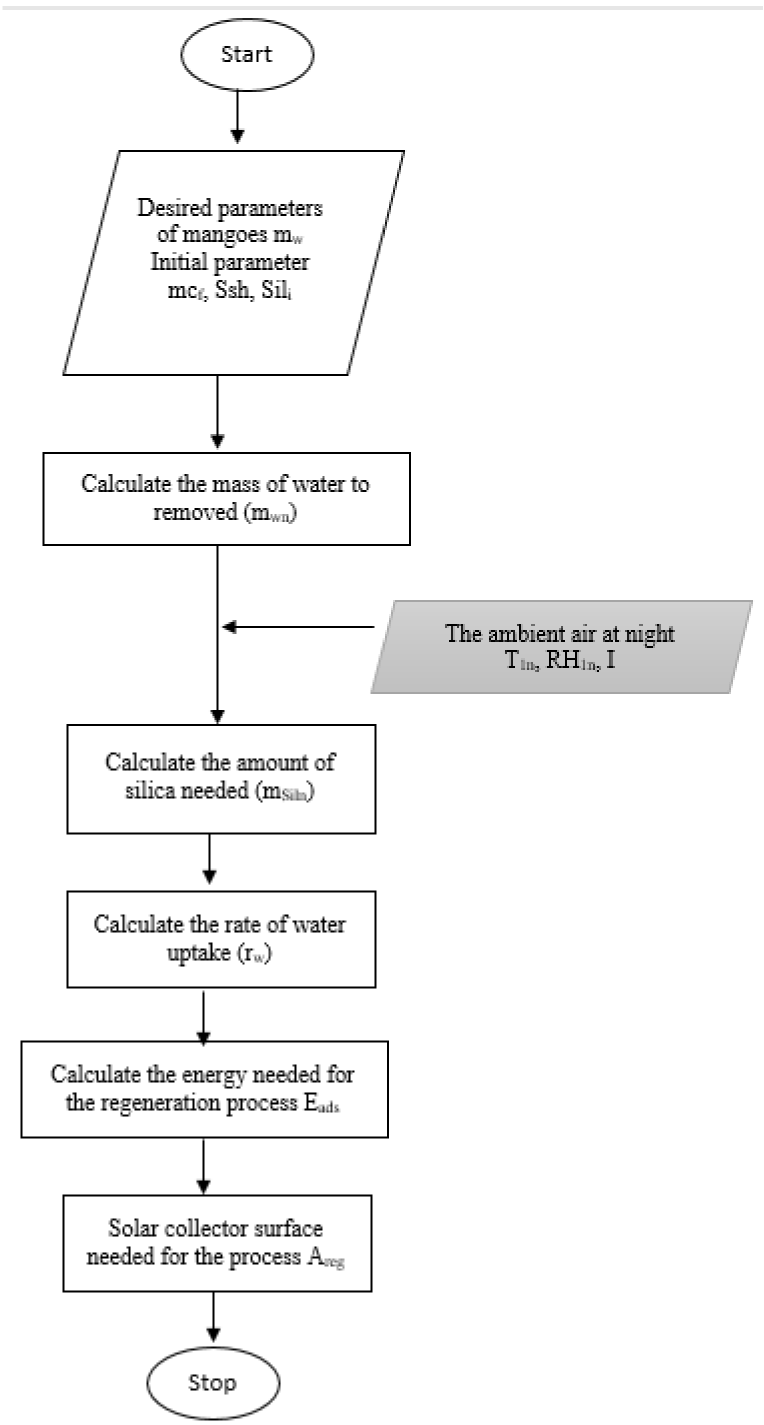

**Figure 17 The storage design tool flowchart**

The storage will start the drying process at the nighttime. Thermal storage developed here uses silica gel material. At night time the air entry will be closed, and the temperature of the air inside the drying chamber $T_{in}$ at the steady state will equal the temperature of the air outside $T_{1n}$. The equilibrium relative humidity of the inside air $RH_{in}$ will be calculated by substituting with Tin in equation (14).

The mass of water to be removed at night ($mw_n$) calculated as [45]

$$mw_n = m_w \text{ x } S_{sh} \tag{18}$$

The same type of silica gel used in the dehumidifier will be used for the storage, the initial moisture content $Sil_i$ equals 2.5 % of its mass, and the final moisture $Sil_f$ calculated [43]

$$Sil_{fn} = 0.6114\ (RH_{in})^{1.2646} \tag{19}$$

The amount of silica gel in the storage $m_{siln}$ will be equal

$$m_{siln} = \frac{mw_n}{Sil_{fn} - Sil_i} \tag{20}$$

The rate of the water uptake $r_w$ (kg/s) calculated as [46]

$$r_w = 0.2163\ (Sil_{fn} - Sil_i)^{\ 0.528} \tag{21}$$

The time required for adsorption process $t_{ads}$ equals to

$$t_{adsn} = \frac{mw_n}{r_w} \tag{22}$$

The isotherm correlation for the heat energy of adsorption $E_{ads}$ (J/kg ) calculated as [46]

$$E_{ads} = \{ \begin{array}{ll} -12400\ (Sil_{fn} - Sil_i) + 3500 & (Sil_{fn} - Sil_i) < 0.05 \\ -1400\ (Sil_{fn} - Sil_i) + 2900 & (Sil_{fn} - Sil_i) > 0.05 \end{array} \tag{23}$$

The silica gel will regenerate using solar energy, and the area of the solar collector used for regeneration area ($m^2$) is equals

$$A_{reg} = \frac{E_{ads}}{\eta\ I} \tag{24}$$

## 3.4 Model initial Evaluation

To evaluate the model, different calculations had been performed in spreadsheets as summarized in Table 3. The aim was to determine the solar drying system size using the average ambient conditions in the harvesting season.

**Table 3 The simulations performed for the model evaluation**

| Case number | |
|---|---|
| 1 | Common ideal drying process |
| 2 | Common real drying process |
| 3 | A dehumidifier is introduced |
| 4 | The drying was made was sorption material |
| 5 | A thermal storage with a dehumidifier are introduced in the process |

Case n° 1. The first calculation was done for the case of an ideal dryer, i.e. the outlet air from the drying chamber is fully saturated or the exhaust gas reaches equilibrium with the mangoes. This implies extremely high and mass transfers since the driving forces for heat and mass transfer would be very low, Because the drying needs to be performed in less than 24 h and sunshine lasts only 12 h. the duration considered in the case is 12 h.

Case n° 2. In the second calculation, exhaust temperature is set above its dew point in order to increase the driving force, reduce the size of the dryer and avoid condensation. typical values of the exhaust air approach are in the range of 20 -25 °C [47] as experimentally observed on mangeos dryer in Burkina Faso by Bounou [48] . We have used 20 °C.

Case n° 3. The third calculation corresponds to a dryer, as described in the second case, with a dehumidifier installed before the solar collector. Either the size of the bed (amount of the required sorption material) or the desired outlet air relative humidity could be set. For illustration purpose, we set the amount of material to 25 kg of dried silica gel. The final size of the bed would be the result of an optimization of the prototype including, among other thing, the cost of the material.

Case n°4. The fourth calculation corresponds to a drying process only handled by a sorption material. The capacity of the bed should be able to remove the whole moisture contained in the mangoes.

Case n°5. The fifth calculation corresponds to a dryer, as described in the third case, with a thermal storage coupled to the drying chamber. it is assumed that the storage would remove the surface free water during 12 hours and the linked water will be removed by the coming energy directly from the solar collector during sunshine.

# CHAPTER FOUR: RESULTS AND DISCUSSION

Spreadsheets simulation was used to evaluate the model. The average ambient temperature and humidity were used in the spreadsheet calculation. Simulation give insight about the different dryer components size, the required solar collector area, the necessitated silica gel weight. The simulation provides the time and the energy needed for silica gel regeneration process. After that hourly measured climate data was used in matlab code to get more accurate dimensions for the solar drying system compared to spreadsheets results, the aim was to provide the dimensions for a solar dryer which can effectively work on the whole harvesting season.

## 4.1 The Simulation of Climate Data

The harvesting season of mangoes starts from April to June in Burkina. The hourly temperature recorded in the harvesting season in 2013. Figure 18 represents the average value of the temperature in the day. It is clear that the temperature is not so high and the peak at 4 pm is 30 °C. Figure 18 represents the daily measured relative humidity. The relative humidity at the day ranges between 80 % at 7 am to 62 % at 7 pm. The average is 72 %, which is quite high value.

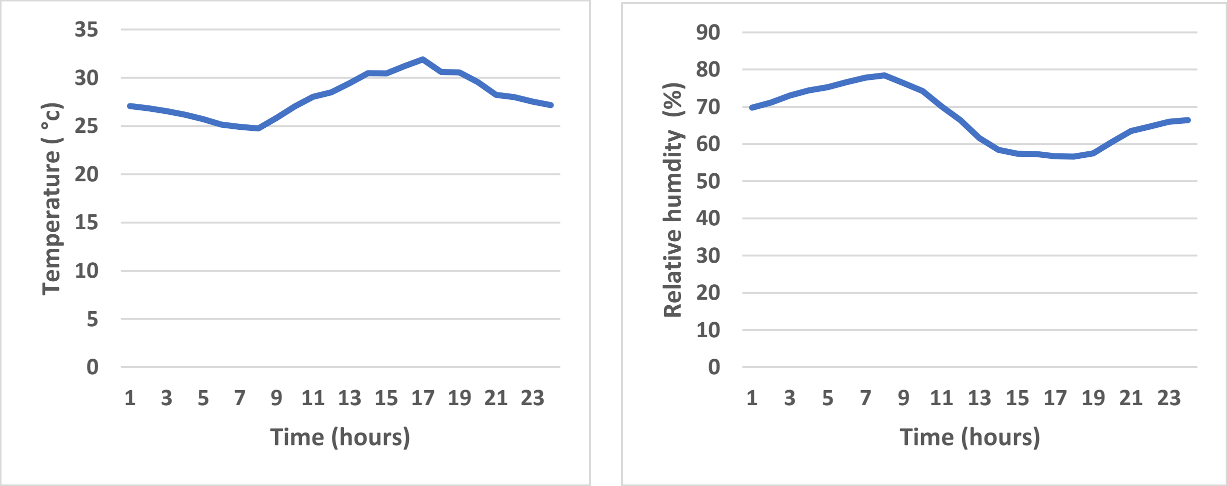

**Figure 18 The average temperature and relative humidity in typical day in Bankandi**

Figure 19 is a detailed look on the measured global horizontal irradiation in the harvesting season over the day, it shows that the solar irradiation is available from 7 am to 7 pm with peak equals 500 W/m$^2$ at 2 pm.

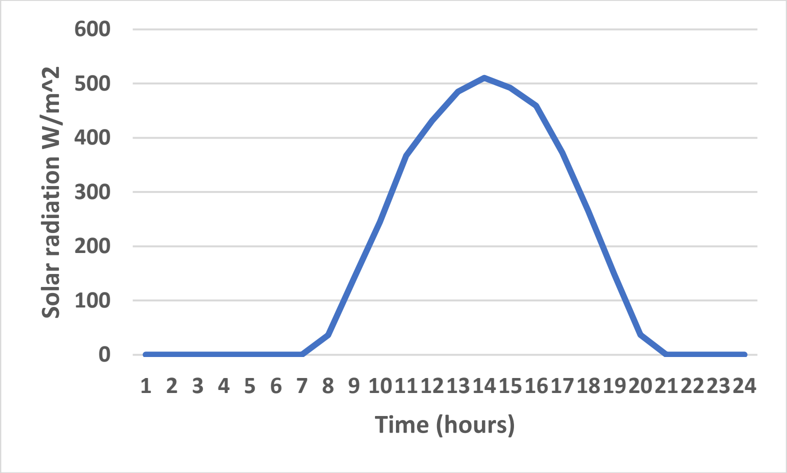

**Figure 19 The global horizontal solar radiation in Bankandi**

## 4.2 The Model Evaluation

### Case n°1. Common ideal drying process

The results of the simulations with an ideal dryer are presented Figure 20 and Table 4 . It appears that about 38.1 m$^2$ of collector surface is required to ensure the drying of 100 kg of mangoes using on within 24 h. This collector surface area is, a priori, relatively large.

**Table 4 Simulation results of case n° 1**

| | | |
|---|---|---|
| Initial mass of water | 85.0 | kg |
| Mass of solid | 15.0 | kg |
| Final mass of mangoes | 17.6 | kg |
| Final mass of water in the mangoes | 2.6 | kg |
| Mass of water to be removed | 82.4 | kg |
| Wet bulb temperature in the dryer | 31.0 | °C |
| Temperature of the air at outlet of the dryer | 31.0 | °C |
| Drying rate | 6.9 | kg water/h |
| **Mass flow rate of air** | **686.7** | **kg air /h** |
| **Needed energy to evaporate water** | **247200.0** | **KJ** |
| **Area of collector** | **38.1** | **m^2** |

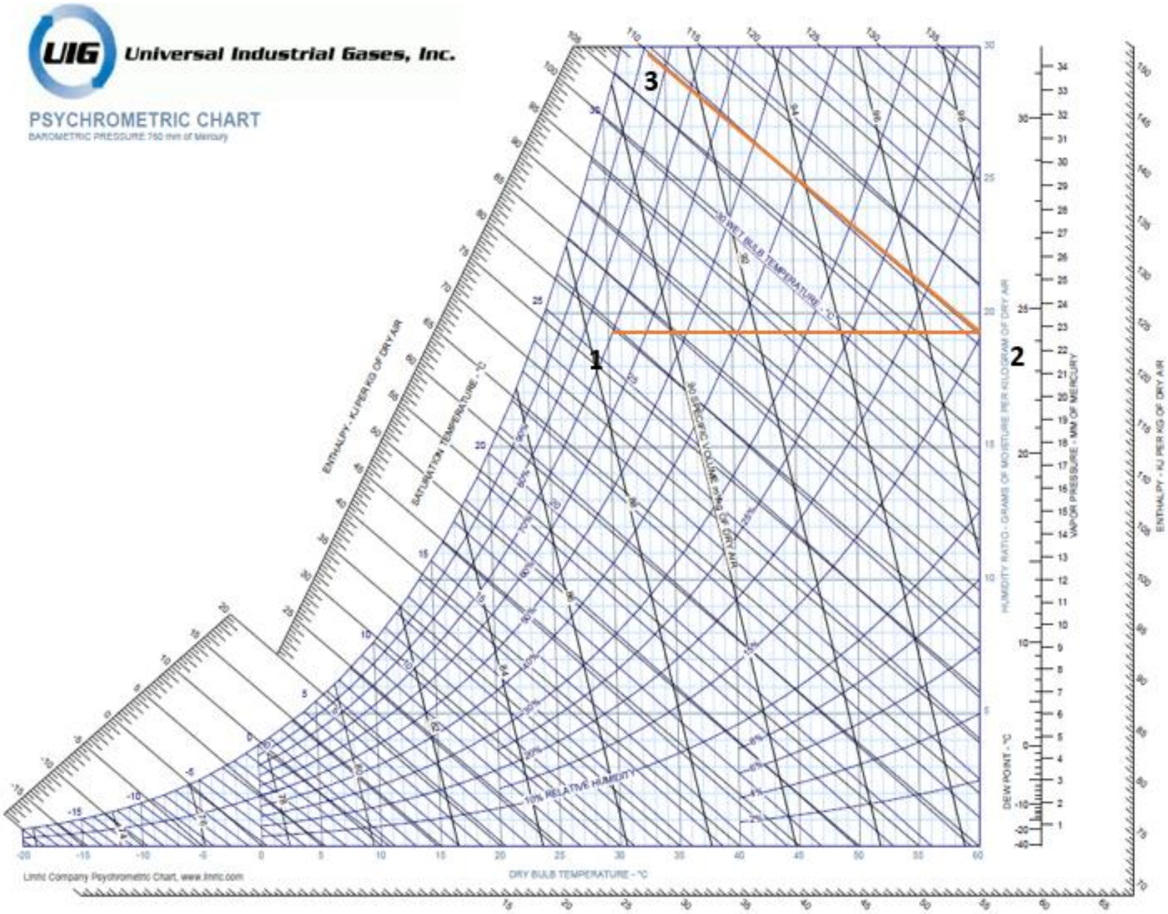

Figure 20 The process of case n° 1

## Case n °2. Common real drying process

In this case, the required surface area of collector is multiplied by 3 as the amount of air to be circulated also increases threefold as shown in Table 5 and Figure 21. As significant amount of energy is indeed taken away from the air exiting the drying chamber. A recovery of that heat could be imagined either for the regeneration of the sorbent beds or to increase the temperature of the inlet air while avoiding condensation.

**Table 5 Simulation results of case n° 2**

| | | |
|---|---|---|
| Initial mass of water | 85.0 | kg |
| Mass of solid | 15.0 | kg |
| Final mass of mangoes | 17.6 | kg |
| Final mass of water in the mangoes | 2.6 | kg |
| Mass of water to be removed | 82.4 | kg |
| Wet bulb temperature in the dryer | 31.0 | °C |
| Temperature of the air at outlet of the dryer | 51.0 | °C |

|  |  |  |
|---|---|---|
| Drying rate | 6.9 | kg water/h |
| **Mass flow rate of air** | **2288.9** | **kg air /h** |
| **Needed energy to evaporate water** | **824000.0** | **KJ** |
| **Area of collector** | **127.2** | **m^2** |

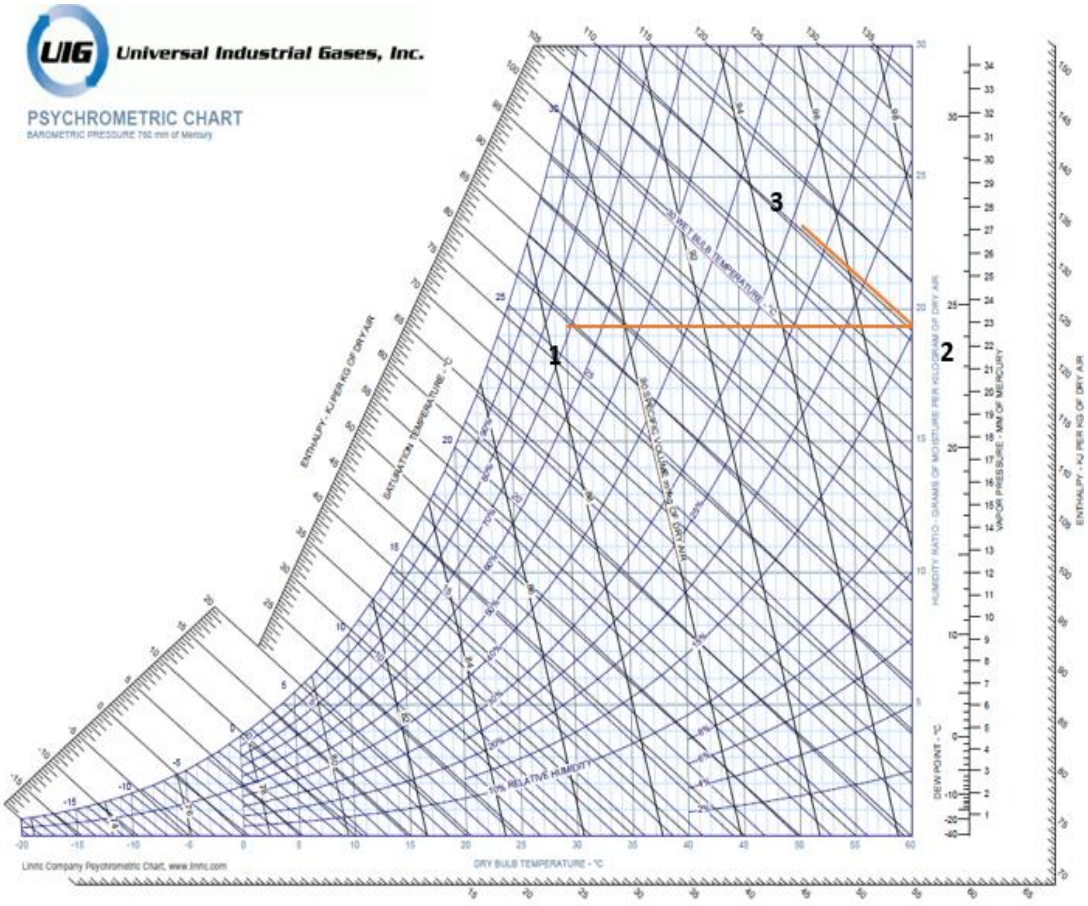

**Figure 21 The process of case n° 2**

## Case n3. A dehumidifier is introduced

The results of the simulations with a dehumidifier are presented in Table 6 and Figure 22 . It appears that about 50.9 m$^2$ of collector surface is required to ensure the drying of the desired amount of mangoes.

**Table 6 Simulation results of case n° 3**

|  |  |  |
|---|---|---|
| initial mass of water | 85.0 | kg |
| Mass of solid | 15.0 | kg |
| final mass of mangoes | 17.6 | kg |
| final mass of water in the mangoes | 2.6 | kg |
| mass of water to be removed | 82.4 | kg |

| | | |
|---|---|---|
| Wet bulb temperature in the dryer | 31.0 | °C |
| temperature of the air at outlet of the dryer | 42.0 | °C |
| drying rate | 6.9 | kg water/h |
| **mass flow rate of air** | **1125.7** | **kg air /h** |
| **needed energy to evaporate water** | **329600.0** | **KJ** |
| **Area of collector** | **50.9** | **m^2** |

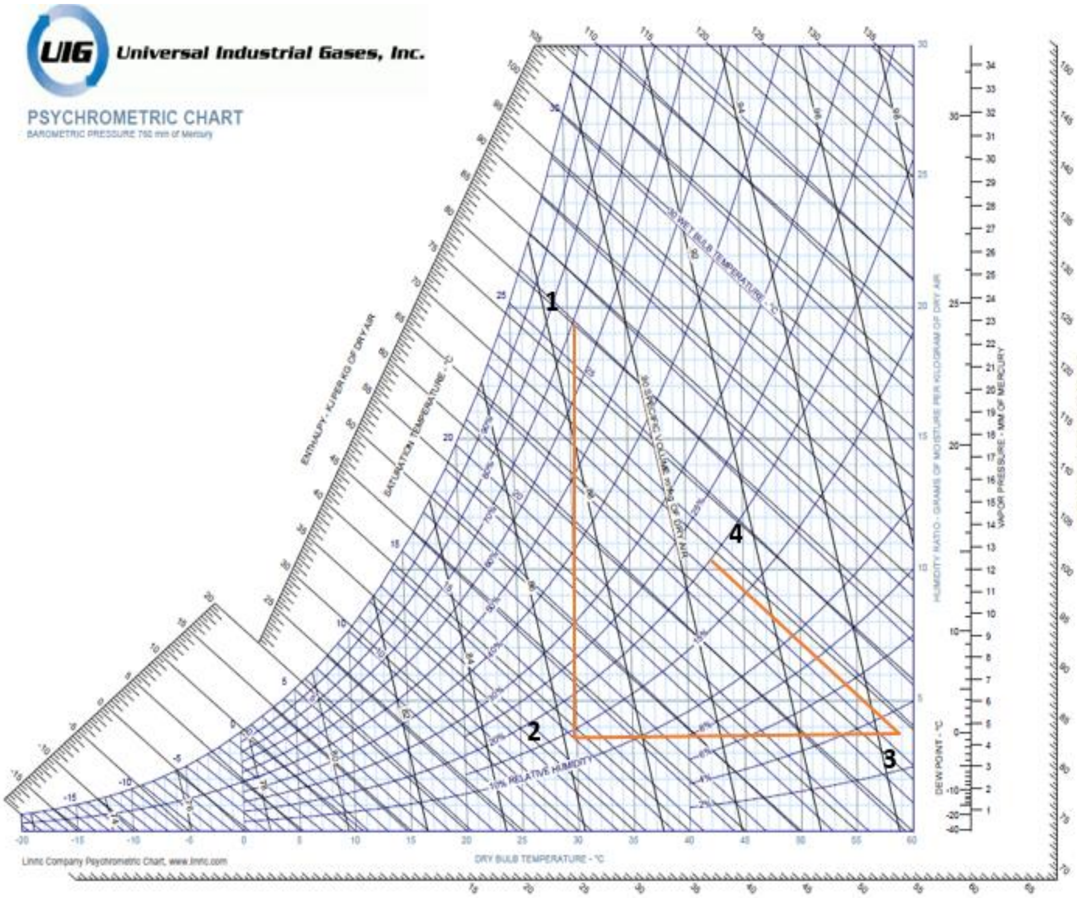

**Figure 22 The process of case n° 3**

## Case n° 4 . The drying is made with a sorption material

The results of the simulations with the sorption storage are presented in Table 7 . It appears that about 0.27 m3 of the material is required to ensure the drying of the desired amount of mangoes, considering that the silica gel reaches the equilibrium at 40% of its volume.

**Table 7 Simulation results of case n° 4**

| | | |
|---|---|---|
| initial mass of water | 85.0 | kg |
| Mass of solid | 15.0 | kg |
| final mass of mangoes | 17.6 | kg |

| | | |
|---|---|---|
| final mass of water in the mangoes | 2.6 | kg |
| mass of water to be removed | 82.4 | kg |
| initial water content in silica gel | 0.025 | kg/kg |
| final water content in silica gel | 0.4 | kg/kg |
| density of the sorbent | 800.0 | kg/m^3 |
| equilibrium relative humidity of the dried mangoes | 0.5 | % |
| **required mass of sorption material** | **218.1** | **kg** |
| **volume of sorption material** | **0.272649** | **m^3** |

**Case n°5. A thermal storage and a dehumidifier are introduced in the process**

The results of the simulation in that case are presented in Table 8 and Figure 23. It appears the material volume decreased to 0.2 m3 compared to case n° 4. The collector surface required was 16.9 m2 and this value is also less case n° 1. Applying both conditions will ensure the drying of the desired amount of mangoes in the desired time. The results here show that case n° 5 is the best design compared to the other cases.

**Table 8 Simulation results of case n° 5**

| | | |
|---|---|---|
| initial mass of water | 85.0 | kg |
| Mass of solid | 15.0 | kg |
| final mass of mangoes | 17.6 | kg |
| final mass of water in the mangoes | 2.6 | kg |
| total mass of water that must be removed | 82.4 | kg |
| mass of water to be removed at the nighttime | 14.8 | kg |
| drying rate in the morning | 5.6 | kg/h |
| drying rate in the night | 1.2 | kg/h |
| initial water content in silica gel | 0.025 | kg/kg |
| final water content in silica gel | 0.4 | kg/kg |
| density of the sorbent | 800.0 | kg/m^3 |
| equilibrium relative humidity of the dried mangoes | 0.535 | % |
| **required mass of sorption material in the dehumidifier** | **39.3** | **kg** |
| **volume of sorption material in the dehumidifier** | **0.0490769** | **m^3** |
| **required mass of sorption material in the storage** | **162.13178** | **kg** |
| **volume of sorption material in the storage** | **0.2026647** | **m^3** |
| **mass flow rate of air** | **557.5** | **kg air /h** |
| **needed energy to evaporate water** | **194007.1** | **KJ** |
| **Area of collector** | **29.9** | **m^2** |

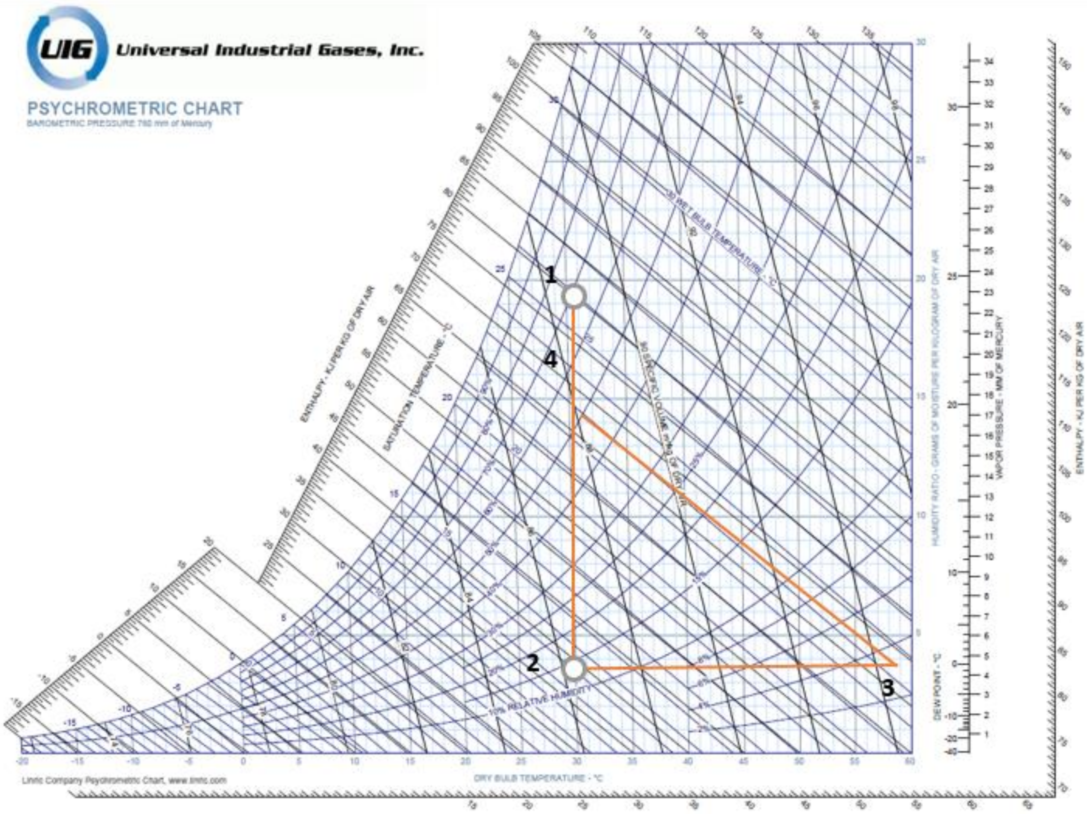

Figure 23 The process of case n° 5

## 4.3 The Model Simulation in Matlab

The measured hourly air properties used in the model. The required solar collector area calculated for each hour during the five harvesting months because the amount of mangoes to dried is very large so we think that it is possible to continue drying the mangoes after Amelie harvesting season. the results are as shown in Figure 24 clear show that depending on the average climate data may lead to ineffective drying system in the whole season.

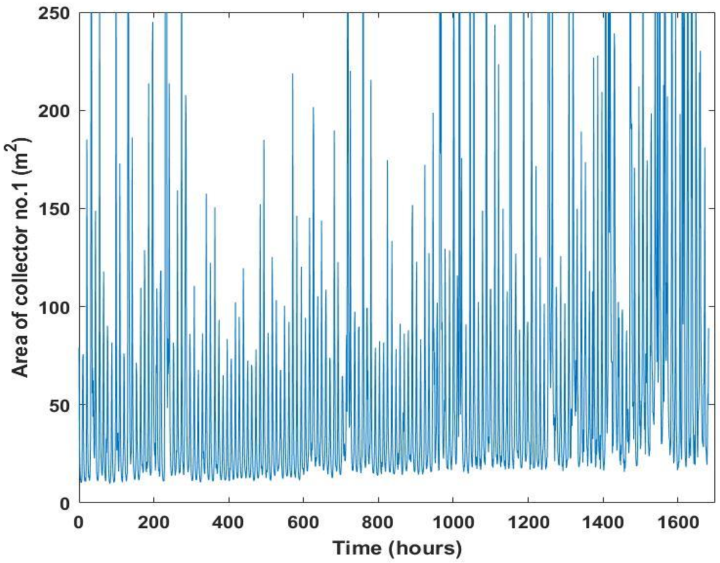

**Figure 24 The required solar collector area**

Around 254 kg of silica gel required for the air dehumidification unit and 40 kg for the storage on average are needed in the drying system shown in Figure 25.

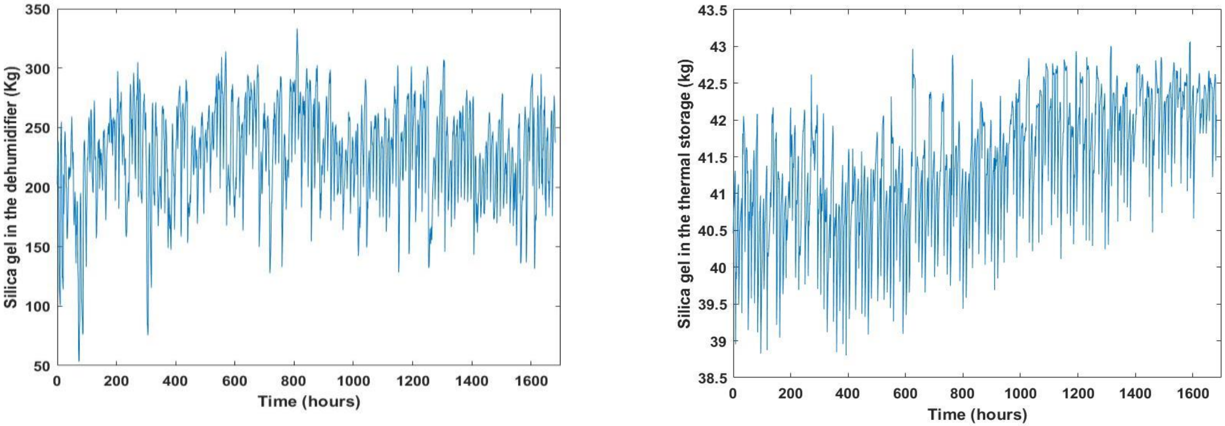

**Figure 25 The silica gel weight in the dehumidifier and the thermal storage**

The rate of adsorption is significant to be calculated so we can know whether the silica gel will be able to adsorb the water in the working hours or not. The simulation result for the adsorption rate in the dehumidifier Figure 26 . Also, from the calculations, the adsorption process needs12 hours.

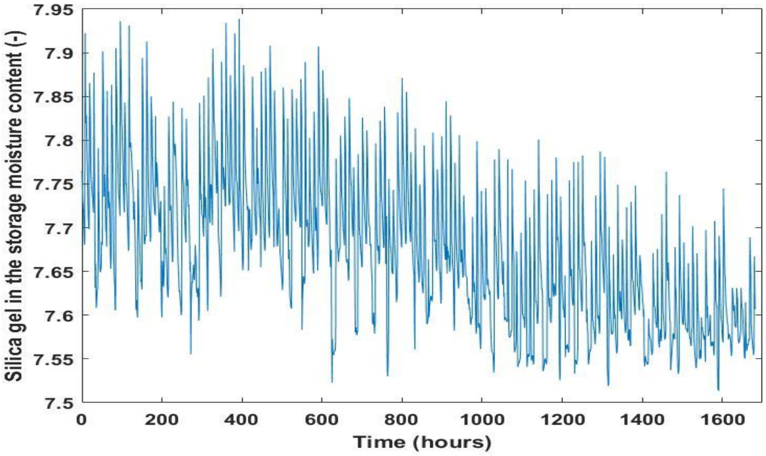

**Figure 26 the rate of adsorption**

# Chapter five conclusion and recommendations

## 5.1 Conclusion

Drying mangoes in Burkina Faso can be done using solar dryer. The dryer should have a dehumidifier and built-in storage so that it can be an excellent competitor to gas-fired dryers during the rainy season. These additives will decrease the entry air humidity level, which will consequently decrease the required drying time.

The drying process should start at night and continue in the following morning. The working strategy of the suggested dryer at the daytime is, the ambient air will be dehumidified and heated before entering the drying chamber, when the air will get statured it will exit the drying chamber. The aim in the morning hours is to get rid of the linked water in the mangoes slices. The drying system will work differently at the nighttime; no air will enter or exit the drying chamber. The thermal storage will heat the inside air and adsorb its humidity at the same time; the role of the storage is to absorb the surface water in the mangoes.

The storage will be regenerated in the following morning and it is one storage that will be used every night in the drying system. Two beds of silica gel are suggested for the dehumidifier, so that one will be regenerated while the other one is embedded in the drying system. Every morning, the saturated bed will be replaced by the other bed manually.

This work provides three designing tools, one for the dehumidifier, the second for the storage and the last for the solar collector which is connected to the drying chamber. Each tool gives insight about the drying system size in any climate conditions. The tools required the desired specifications like drying capacity, desired moisture in the mangoes, drying time, maximum drying temperature, the initial moisture content in both the mangoes and silica gel and the site climate conditions for calculating the required collector surface area, the amount of the material needed for both the storage and dehumidifier. The tools are helpful to those interested in designing solar dryer.

Both spreadsheets and Matlab simulations were used to size the solar dryer system. In spreadsheet simulations, the average value of the climate conditions was used to evaluate the solar dryer model and to determine the initial drying system size. After that, the hourly measured climate data was used in Matlab simulation to calculate the required dryer size. The objective of the Matlab simulation was to get more accurate system size.

The suggested solar dryer system consists of 20 $m^2$ solar collector, thermal storage has 40 kg of silica gel, and two dehumidifier beds each has 253 kg of silica gel. The dryer capacity is 100 kg of mangoes, and the drying time is 24 hours. The fastest model was done in Burkina Faso was a hybrid solar dryer, and it required 36 hours for drying the same amount of mangoes.

Silica gel is the best to be used in the solar dryer system in Burkina Faso because it can be regenerated using sun radiation only. Also, according to the simulation results, the morning hours will be sufficient for the regeneration process.

## 5.2 Recommendations

- A study for the heat and mass transfer in the dryer should be done
- Simulation for the drying process should be done with considering the kinetics aspect and thermal losses.
- The feasibility study should be done for the proposed design to determine the system economics.

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