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An Overview of Moisture Removal Mechanisms in Small-scale Dryers

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Abstract: *This paper presents an overview of moisture removal mechanisms used for the dehumidification of drying chambers in small-scale drying equipment. These mechanisms are based on the existence temperature gradient or pressure gradient between the entry and the exit of the drying chamber. Dryer design based on those physical effects without using pump or fan lead to natural air circulation and depend on weather conditions. They require too long time to get crops dried due to the fact that the buoyancy forces are not strong enough to dehumidify rapidly the drying chamber. Dryers using motorized fans to force air circulation rely on pressure gradient between the entry and the exit of the drying chamber. Their main limitation is that drying air renewal depends on drying air temperature regardless of its moisture content. In all cases, the geometry of most drying chambers is not properly designed in order to ease the removal of humid air. Important losses are recorded during drying because crops stay in a humid environment for too much time. That problem is more critical in humid tropical zones where ambient air and crops are both high moisture content.*

Keywords: *Moisture, small-scale dryers, pressure gradient, temperature gradient, natural convection, forced convection.*

1. Introduction

Air drying is the most widespread way of processing food crops for long time conservation [1, 2]. Dried products take up much less space than their fresh equivalents, further reducing transport and storage costs [3,4]. Drying of food materials is in principle a fairly simple process: the food is placed in a medium such as air where the partial pressure of water is low and is kept in that environment until the food's water content drops to a desirable level that prevents deterioration within a certain period of time, normally regarded as the "safe storage period" [4]. Generally, crop drying consists of three steps: heating the product, vapourizing water from it and evacuating moist air from arround it.

Transferring heat to the product supplies the energy necessary for the vapourization of water from it [5]. Traditionnaly, heat is transferred to the crop by exposure to sun radiation [2,4,6]. In humid tropical areas, the environment is of high relative humidity, climatic conditions have a great influence on the extent of crop losses and deterioration during sun drying. Crops require an undesirably long period to reach equilibrium moisture content the value of which is insufficiently low for safe storage [7,8]. The objective of a dryer is to supply the product with more heat than is available under ambient conditions, thereby increasing sufficiently the vapour pressure of the moisture held within the crop and decreasing signifficantly the relative humidity of the drying air and thereby increasing its moisture carrying capacity and ensuring a sufficiently low equilibrium moisture content [9,10].

Many research works have been done for the effectiv control of the drying process as far as heating is concerned in order to encrease moisture extraction rate from the crop in one hand and to preserve germinability, color and taste of sensitive crops, to promote the developpement of full flavour, taste, color and perfume of many others [8,9,10,11,12,13,14,15,16]. Less attention has been paid to moisture extraction from the drying chamber. Crop deterioration and losses during drying remains high in tropical humid areas because the remain in a moist environment for too long [6,16,18].

The purpose of this paper is to present the performances of smal-scale dryers according to their moisture evacuation mechanism.

2. Drying Systems Classification

Crop drying begins with temperature setup [4,12,19]. During this period, heating the product leads to the increase of its temperature. This temperature setup continues until the product is in equilibrium with the heating air at the so called 'humid temperature'. From there on, bringing more heat into the drying chamber leads to the vapourization of an amount of water from the product and its transfer to the surrounding air. For a given 'humid temperature' the amount of water vapour that can be carried by a kilogramme of drying air is limited therefore the air surrounding the product must be renewed by air circulation. Before moving into drying system classification according to their moisture extraction mechanism, let's share a common understanding of some keywords. By 'ambient air', we consider ai taken from the environment regardless of its moisture content and its temperature. 'Drying air' refers to an air that the temperature T_a(°C) is superior to the humid temperature T_h(°C) or that the relative humidity RH(%) is inferior to the moisture content X(%) of the crop beeing drying. If T_a(°C) > T_h(°C) heat is transferred from the air to the crop. If RH(%) < X(%) moisture is transferred from the crop to the air. By 'humid air' we call an air that cannot uptake moisture from the crop. In small-scale dryers, air circulation is natural or forced.

2.1. Moisture Removal Based on Natural Air Circulation

Natural air-circulation is mainly based on the existence of temperature gradient or pressure gradient acting solely or in combination in the drying chamber.

2.1.1. Air Circulation Based on Temperature Gradient

Drying systems using temperature gradient to generate air motion in the drying chamber include cabinet dryers, tent or greenhouse dryers and tunnel dryers. **Fig. 1** presents a feature of theese drying systems.

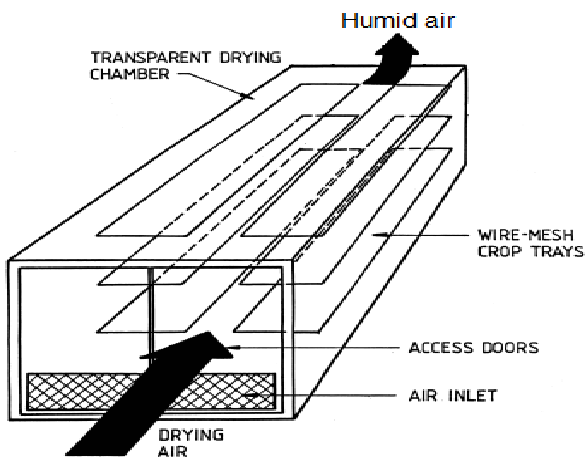

Figure1. *Features of a direct natural-circulation solar-energy dryer.*

They consist of o drying chamber containing crop trays, an air inlet and an air outlet. Fresh crop and ambient air are simultaneously in the drying chamber. As the air inside the drying chamber gets hotter and hotter, its density decreases progressively. Air circulation is therefore initiated based on the difference of density of air particles. Less dense particles adopt an ascending movement while more dense pone move downward.

Most practically-designed use solar-energy with a transparent drying chamber. Direct exposure to sunlight has many advantages as allready described by [20]. **Fig. 2** illustrates the fundamental features of the standard Brace Institute solar cabinet dryer [8]. Also called 'Box type solar dryer', cabinet dryer is suitable for drying of 10–15 kg of fruits, fish, meats and vegetables for household needs [11].

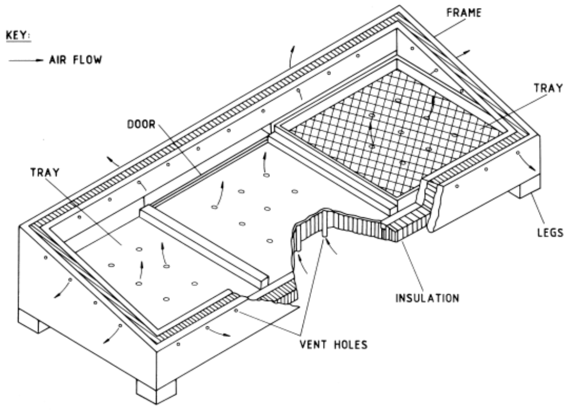

Fig.2. *A typical natural-circulation solar-energy cabinet dryer*

They are single or double-glazed insulated hot boxes with holes at the base and upper parts of the dryer's walls. The solar energy is transmitted through the cover and is absorbed on blackened interior surfaces. Moisture removal is based on air circulation, provided by the warm moist air leaving via the upper apertures under the action of Buoyancy forces while fresh air is drawn from the base. Drying air temperatures reaches 80°C in the drying chamber [14,15]. Cabinet dryers have two major drawbacks: the relatively slow overall drying rates achieved due to poor vapour removal and condensation on the inner face of the dryer due to the difference between drying air temperature and the ambient air temperature in case of single glazed box.

Another practically-designed dryer usig temperature gradient for air circulation is the greenhouse or tent dryer. **Fig. 3** presents a polyethylene-tent dryer [8,21,22]. The dryer consists of a ridged bamboo framework clad with clear polyethylene sheet on the sun facing side and at the ends. The rear side is clad with black polyethylene sheet which is also spread on the floor to improve absorption of solar radiation. The cladding at one end is arranged to allow access into the drying chamber.

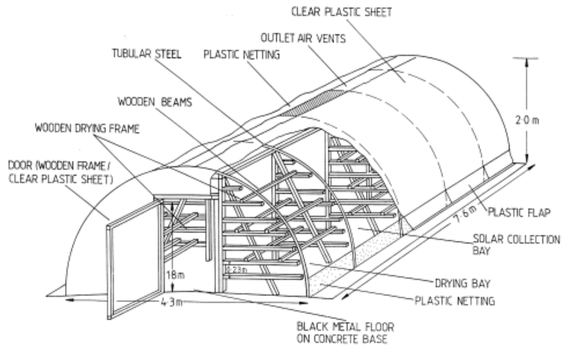

Figure 3. *Natural-circulation solar dome dryer.*

Focusing on air circulation through the dryer, the clear plastic cladding at the bottom edge of the front side is rolled around a bamboo pole which can be adjusted to control air flow into the drying chamber. The air temperature in the drying chamber rises significantly giving way to an increase of its moisture carrying capacity. Humid air is moved upward by Buoyancy forces. The vents at the top of the ends serve as the exit for the moist exhaust air. Regardless of the design of greenhouse dryers, the difference of temperature on their inner and outter faces is such that there is condensation.

Moisture removal based on temperature radient has many inconvenients. Air particles charged with water are heavier, under their weight, they move downward and remain in the drying chamber for too long. In their upward movement, some less dense particles come across the glass in the case of cabinet dryers or the polyethylene where water vapor changes phase and becomes liquid leading to a cyclic situation in which water is vapourized and condensed in the drying chamber. Another important limit is the confusion between the ambient air, the drying air and the humid air in the drying chamber. The outside air gets in when possible, inside air gets out when possible regardless of its temperature or its relative moisture.

2.1.2. Air Circulation Based on Pressure Gradient

To improve air circulation in the drying chamber, a chimney is introduced in the design of drying systems. Its role is to create a pressure gradient between its top and bottom ends therefore increasing the Buoyancy forces imposed on the air stream in order to provide a greater air flow velocity and thus, a more rapid rate of moisture removal. **Fig. 4** presents a feature of a typical natural-circulation governed by pressure gradient. The dryer consists of an air heating unit, a drying chamber and a chimney [8].

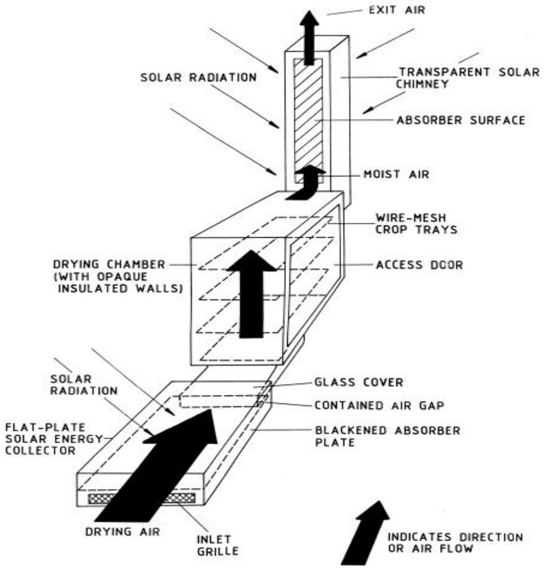

Figure 4. *Features of a typical natural-circulation solar-energy dryer equipped with a chimney*

Ambient air is admited from the environment and introduced in the air heating unit where it receives the required energy before entering the drying chamber. Heating air, increases significantly its temperature thereby increasing its moisture carrying capacity. In the drying chamber, heat is transferred to the crop and moisture extraction takes place. As a result of heat transfer to the crop, air temperature decreases but its value remains high enough to allow it to carry moisture. In the chimney air is once more heated, its upward mouvement is therefore accelerated following temperature difference between air mass from top to bottom areas. Moisture removal from the drying chamber is initiated and sustained by the pumping function of the chimney. Due to its low density and wind action, hot air near the chimney exit moves out. Governed by buoyancy forces, air masses change position moving from the bottom to the top end of the chimney, from the drying chamber to the bottom of the chimney, from the air heating unit to the drying chamber and from the environment to the air heating unit. This air circulation mechanism goes on as far as solar radiation and wind effects are available.

Sun drying falls in this category like dryers equiped with chimney, they include cabinet dryers, greenhouse dryers, biomass dryers, and wind-ventilated solar dryer. Sun drying techniques still remain the most widely used methods for crop drying in the developing countries [8]. It consists of laying produce directly upon trays, rocks, screens or mats, flat black surfaces, allowing the sun and wind to dry the crop. Although these practices are successful in dry season, in humid tropical areas, crops are high moisture content and for many of them, harvesting is done during wet season [23]. Moisture extraction based on solar radiation and wind action is not guaranteed since the relative humidity of ambient air is very high [23,24]. As a result of all this, crop deterioration takes place even during drying. **Fig. 5** illustrates an indirect solar maize dryer reported by [25,26,27]. The dryer consisted of a single-glazed passive solar air heater with a $1m^2$ single flat-plate absorber and an air gap of 5 cm from the glazing. The air heater is connected to an insulated drying bin equipped with a chimney. The crop is located in trays or shelves inside an opaque drying chamber and heated by circulating air, warmed during its flow through a low pressure drop thermosyphonic solar collector [8].

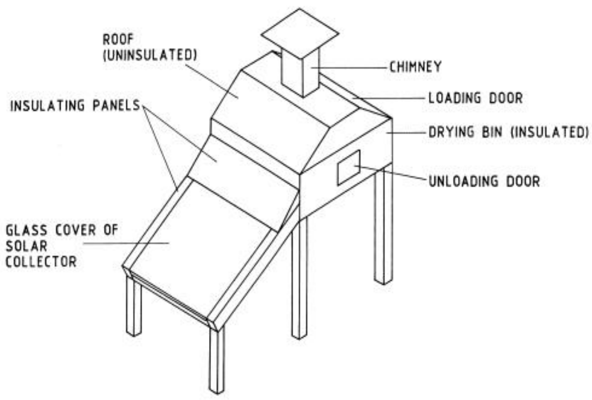

Figure 5. *A distributed-type natural-circulation solar maize dryer*

Because solar radiation is not incident directly on the crop, caramelization and localised heat damage do not occur [25,26]. These dryers are also recommended generally for some perishables and fruits for which their vitamin content are reduced considerably by direct exposure to sunlight and for colour retention in some highly pigmented commodities that are also very adversely affected by direct exposure to the sun [25,26]. This distributed version of the cabinet dryer has a major limitation, the chimney is not heigh enough. As results, the Buoyancy forces do not increase significantly even if these solar dryers have higher operating temperatures than direct dryers or sun drying systems and can produce higher quality products. The dryer is capable to dry 90 kg of wet maize from a moisture content of about 20 % wet basis to 12 % within 3 days on a bright day [8]. **Fig. 6** illustrates a simplified design of the typical greenhouse-type natural-circulation solar dryer reported by [20]. It consists of a transparent semi-cylindrical drying chamber with an attached cylindrical " chimney ", rising vertically out of one end. The other end is equipped with a "door" for air inlet and access to the drying chamber. The chimney has a maximum possible height of 3,0 m above the chamber and a diameter of 1,64 m. The dryer operates by the action of solar-energy impinging directly on the crop within the dryer.

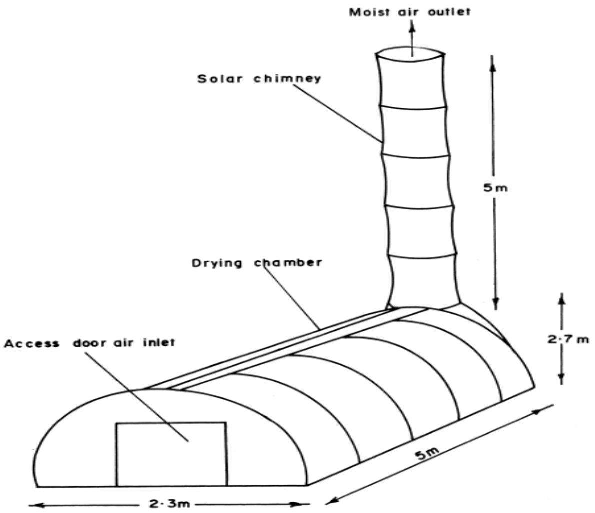

Figure 6. *A simplified design of the typical greenhouse-type natural-circulation solar dryer*

The crop and a vertically-hung, black absorbing curtain within the chimney absorb the solar radiation and are warmed. The surrounding air is then heated, its temperature rises and so does its moisture carrying capacity [27,28]. As this humid air rises and flows up the chimney to the outside of the dryer, ambient air from the environment is drawn in from the other end of the dryer. This simple operation, involving no additional power source, provides the circulation of air through the dryer. This modified version of the greenhouse solar-energy dryer is usually used for large scale crop drying in rural areas. It is characterized by its low cost and its simplicity in both on-the-site construction and operation. Its major limitation is its susceptibility to damage under very high wind speeds [27]. The obvious problem with solar dryers is their inability to work when there is little or no sunlight. The McDowell dryer shown in **Fig. 7** attempts to overcome this problem by combining solar heat and heat from wood burning in a fire box [30]. The termed McDowell dryer is a modification of the typical solar-energy dryer by introduction of a biomass burning unit. The McDowell dryer consists of a biomass burning unit, a drying chamber and a chimney. A gap separates the furnace from the drying chamber in order to avoid any crop contamination by smoke or by ashes during the drying operation. As the performances of the typical greenhouse and its modification by introduction of a chimney are already previously presented, our attention will be focused on the running of the dryer in absence of sunlight. In that case, the necessary heat for crop drying is produced by burning wood or grass in the biomass burning unit. Fresh air is admited from the environment via the air inlet door.

Heated air and the smoke move into a long metal pipe below the tray of food and exits via a chimney. Fresh air is admited from the environment by help of vent holes. As hot air circulates in the pipe, air in contact with its external surface is heated in turn and moves upward. The crop is heated by conduction via the tray or by convection by direct contact with the drying air.

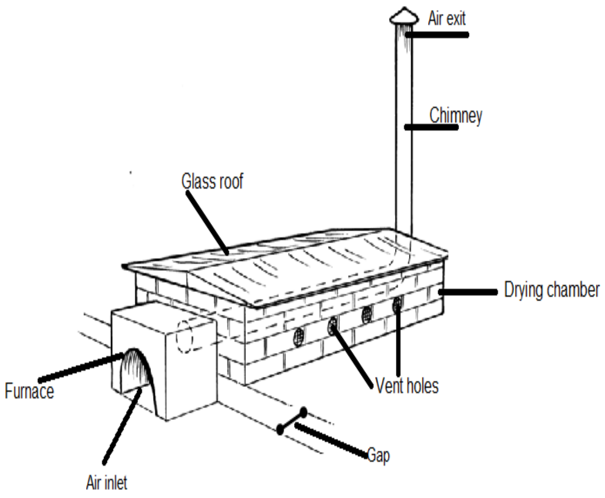

Figure 7. *McDowell solar heat and heat from biomass dryer*

In terms of moisture removal performance of the McDowell dryer, no report is available in the literature. Two major limitations can be identified as far as the functionning of the McDowell dryer in absence of sunlight is concerned. First, considering that during night or in case of rainfall, ambient air temperature is very low while in the drying chamber the air temperature is high, there will be condensation on the interior face of the glazed roof. The rate of drying will certainly decrease. Secondly the extraction of humid air from the drying chamber via vent holes is not governed by Buoyancy forces, there will have condensation on the ground inside the dryer.

Another step towards greater efficiency in terms of moisture removal is the introduction of ventilators which depend only on the wind effect. The so called mixed-mode natural-circulation solar-energy dryer consists structurally in an air heating unit, a drying chamber, a chimney and a ventilator. **Fig. 8** illustrates the design of the wind-ventilated mixed-mode solar dryer. This design differs from all those already presented in this paper by the fact that air circulation is not only governed by Buoyancy forces but also by wind-powered rotary vanes located on top of the dryer chimney.

Under the cumulative effect of the chimney and the ventilator, fresh air is drawn from the environment and moves into the heating unit where its temperature and its moisture carrying capacity increase significantly. In the drying chamber, heat is transferred from the drying air to the crop while moisture is transferred from crop to the drying air.

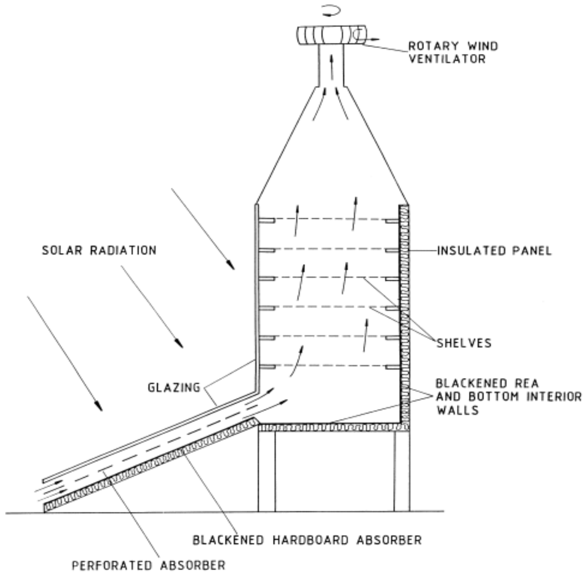

Figure 8. *Mixed-mode wind-ventilated solar dryer*

As a result of those transfers, drying air temperature decreases and its density increases in the same time. Under Buoyancy forces alone, the outgoing movement of humid air will take place at low velocity but with the driving effect of the ventilator, air-circulation is made easier. To increase air natural-circulation in the drying chamber, additional heating is obtained from direct absorption of solar radiation by the crop and the drying air through transparent sheets which cover the south, east and west sides of the drying chamber, for a location with a south facing collector orientation. The rear vertical and bottom panels of the dryer are blackened hardboard, which is insulated to reduce these losses. The base of the chimney is conical, its top end is a cylindrical stack. The conical part of the chimney creates a low pressure area into which the exhaust air is drawn, accelerating the ejector action. The stack requires an appropriate length to achieve the chimney effect and “ catch” more wind.

Natural-circulation solar-energy dryers appear the most attractive option for use in remote rural locations. Their drying period is shortened compared with open air drying, thus attaining higher rates of product throughput. In terms of moisture removal capacity, these dryers can only develop low Buoyancy forces making them completely dependent of the climatic conditions.

3. Moisture Removal Based on Forced-air Circulation

In order to work day and nigth, independently of the weather conditions, forced air circulation systems are developped. They employ solar-energy, electricity and fossil-fuel to motorize fans orpumps for air circulation. The use of fans or pumps aims at developping a greater pressure gradient between the inlet and the outlet of the drying chamber leading to a very important air velocity. As result of forced- air circulation high moisture removal rate from the drying chamber is awaited. According to their moisture removal mechanism, motorized dryers can be classified into three groups depending on the position of fans / pumps.

3.1. Air Inlet Located Fans

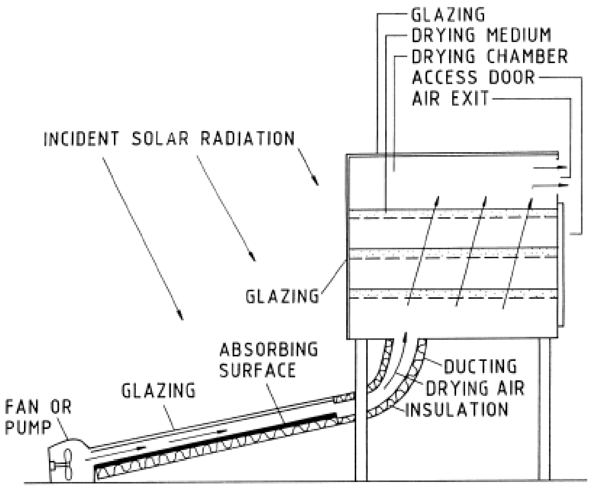

Figure 9. *Features of a typical mixed-mode active solar energy dryer*

Many practically-designed active dryers have their fans and/or pumps positionned in such a way that they blow air from the heating unit into the drying chamber. **Fig. 9** illustrates a modified version of the cabinet solar-energy dryer comprising four basic units: an air heating unit, a drying chamber, a fan and/or pump and a ducting [8].

Since air heating and air temperature are to be contolled, we will focused on moisture evacuation from the drying chamber. Moisture in the drying chamber comes from the ambient air and the crop. The functionning of the dryer is governed by the fan or the pump. When powered, the fan admits fresh air in the environment and forces it into the heating unit first, into the drying chamber then. The fan action continues until the complete renewal of the air formelt present in the drying chamber. The crop and the drying air are heated simultaneously in the drying chamber and the moisture extracted from the crop is picked up by the drying air. In the duct, we have hot air, moving at high speed with greater moisture carrying capacity. Air movement changes significantly in terms of velocity as it moves from the ducting to the drying chamber. The duct has a small diameter, air velocity is therefore very high. In the drying chamber, the section is very large, air velocity decreases a lot. We assist to an important increase of pressure at the bottom of the dryer. As humid air moves up towards exit, its velocity decreases as it comes across trays or shelves. The heat distribution and the moisture collection circuits are not clearly defined. Moisture extraction from the drying chamber is poor. As a consequence of all this, crops located on lower trays receive hot and dry air while those on upper trays recive more humid air. The characteristics of dried product will depend on their position in the dryer. To overcome the problem encountered with the number of trays, **Fig. 10** illustrates typical features of forced-air circulation greenhouse dryer used for commercial drying equiped with a single tray.

These are solar drying designs in which the solar-energy collection unit is an integral part of the entire system thus, no special duct to conduct the drying air to a separate drying chamber is required. Drying air is horizontally forced into the drying chamber by motorized fans or pumps located at the drying chamber base. As drying air continues to be forced into the drying chamber, humid air initially present in the dryer is pushed upward and finally out. This kind of dryer has two major limits.

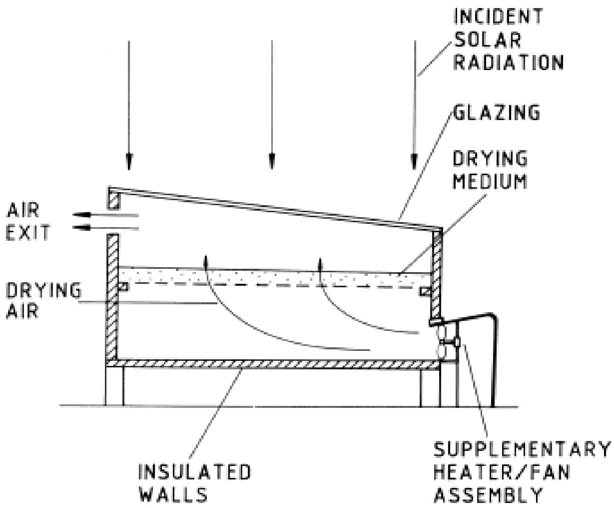

Figure 10. *A forced-convection greenhouse dryer.*

First, during dayligth, there will be condensation on the inner face of the dryer. Secondly, the geometry of the drying chamber does not favour the extraction of moist air by introduction of new. **Fig. 11** illustrates a modified design of the greenhouse solar dryer called solar-energy tunnel dryer.

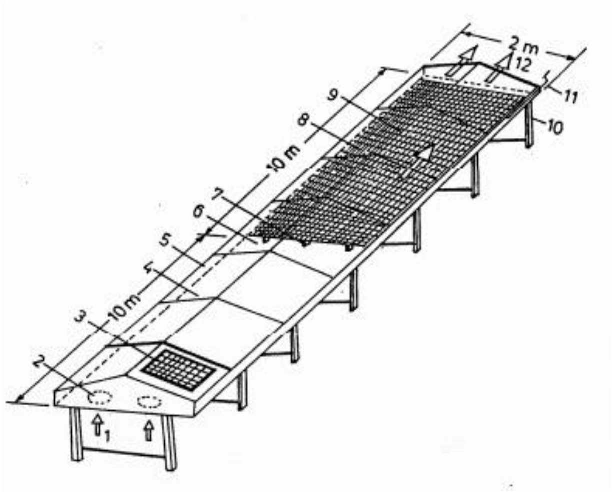

Figure 11. *Solar tunnel dryer*

1. air inlet, 2. fan, 3. solar module, 4. solar collector, 5. side metal frame, 6. outlet of the collector, 7. wooden support, 8. plastic net, 9. roof structure for supporting the plastic cover, 10. base structure for supporting the tunnel drier, 11. rolling bar, 12. Outlet of the drying tunnel

The dryer constists of a flat plate air heating collector, a tunnel drying unit and three small fans. Compared to the typical feature of greenhouse solar-energy dryers, tunnel dryer are built close to the ground, and usually able to hold one layer of produce [9,31,32]. Both the collector and the drying units are covered with uv stabilized plastic sheets. Black paint is used as an absorber in the collector. Glass wool is used as insulation materials to reduce the heat loss from the bottom of the drier. The whole system is placed horizontally on a raised platform. Solar radiation passes through the transparent cover of the collector and heats the absorber. Air circulation in the dryer can be presented as follows: fresh ambient air is admited from the environment and forced through the collector at required flow rate by fans operated by one photovoltaic module. Solar radiation passes through the transparent cover of the dryer, it heats the products and the absorber in the drier. Heated product transfers part of its moiture to the environment. Heat is transferred from absorber to air in the collector and heated air from collector while passing over the products absorbs moisture from the products. As the air is passed over the products rather than through the products in the drier, the power requirement to drive the fans is low. Reported performances of this dryer used to dry fish, mangoes, tomatoes, vegetables by [24,33,34] show that the temperature in the dryer rises in the ranges of 37 °C to 66.5 °C. Comparison of the moisture content of pineapple in the solar tunnel dryer with those obtained by the traditional method for the variety Giant Kew for a typical experimental run during drying at Bangladesh Agricultural University, Mymensingh, Bangladesh shows that the solar tunnel drying required 3 days to dry pineapple samples from 87,32 % to 14,13 % as compared to 87,32 % to 21,52 % in 3 days [31] if dried traditionnally. In the same way, the solar tunnel drying required 3 days to dry mango samples from 78.87 % to 13.47 % as compared to 78.87 % to 22.48 % in 3 days [31]. The use of tunnel dryer during rainy season may lead to very long drying time exposing short shelf life crop to deterioration during drying. **Fig. 12** illustrates typical features of cooking gas dryer [35]. They consist of three rooms among which an air heating room, a drying chamber and an accessory room [12].

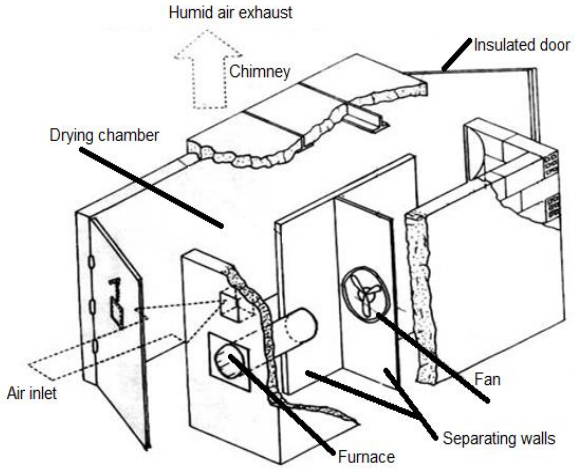

Figure 12. *Typical features of cooking gas dryer*

The first room is the air heating unit. It has an ambient air inlet, a furnace equiped with a cooking gas burner and a hot air outlet governed by a motorized fan. A wall containing a hole inside which is inserted the fan separates that room from the next one. The second room is a drying chamber located in such a way that hot air extracted from the air heating unit can impinge the crop if needed. The third room is a second drying chamber separated from the first one by a removable wall and designed in such a way that no impingment is possible with the crop. It bears a chimney for humid air exhaust. The pressure is developped by the fan and the chimney. Drying air is admited from the environment and heated in the first room. As results, its temperature rises to the required value and its moisture carrying capacity also increases significantly. Forced by the ventilator, drying air is extracted from the heating unit and introduced in the drying rooms where it carries moisture extracted from the crop. The residency time of the drying air in the drying chambers is very short as fan works at high speed. Since heating is done by cooking gas and not by solar energy, blowing blindly air into the dryer without and evluation of the heat carried by a kilogramme of air as it enters the drying chamber and the moisture taken as air runs out may result in an unacceptable consumption of heat and power.

Nut crops can be dried in bulk using a dryer with an external source of heat [9]. The plenum chamber below the produce is covered with a floor of perforated sheet metal or wooden slats. A fan located between the furnace and the plenum chamber moves the hot air through the drying chamber. Practically-designed construction of these dryers use axial fans or pumps located before the drying chamber is the oil-burning dryer as illustrate **fig. 13** [9] and **fig. 14**.

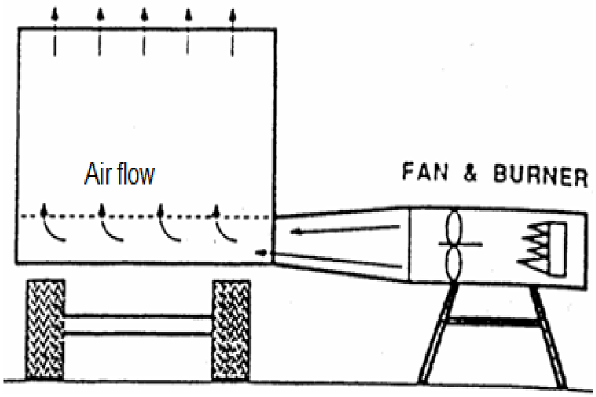

Figure 13. *Typical feature of wagon dehydrator.*

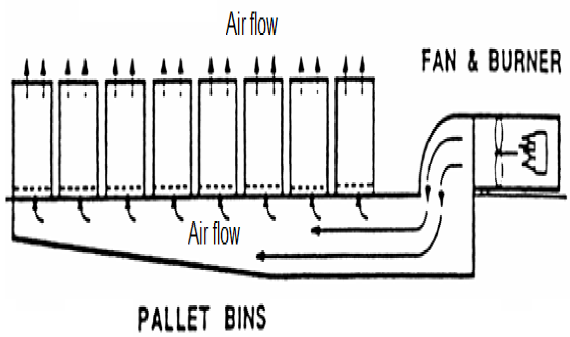

Figure 14. *Typical feature of pot-hole Dehydrator*

Two types of these dryers are commonly used for drying small volumes of nut crops. A wagon with a perforated floor can be transported from the field and connected to a portable burner batch drying. A stationary "pot-hole" dehydrator is designed to move heated air along a plenum under a fixed platform individual bins of nuts are placed upon the platform and are dried as heat rises up through the perforated floor.

Air circulation in these dryers is completely governed by the action of a motorized fan. As it moves at high speed, fresh air is admited from the environment and heated in the furnace. Its temperature rises to the required value, so is its moisture carrying capacity. Drying air is then forced into the drying chamber where heat and moisture diffusion are favoured by stirring regularly of the crop. As the action of the fan continues, air previously present in the drying chamber is forced out with the moisture. The shortcomings, however, are the complexity of equipments in terms of regulation for two reasons. First, the residency time in of the air admited from the environment in the furnace is very short since fans work at high speed. Second, stirring nut crops is fully part of the efficiency of the dryer since it garanties air and moisture circulation.

3.2. Air Outlet Located Fans or Pumps

Some practically-designed dryers are equiped with fans or pump located at air exit. In those cases, the pressure difference responsible of the air movement between the entry and the exit of the drying chamber is obtained as follows. When the fan/pump is powered, it communicates to the air in the drying chamber a high velocity while moving it out. The pressure at the drying chamber exit decreases significantly compared to the pressure at the drying chamber air inlet. We assist to an ai movement from the entry to the exit of the drying chamber. This situation continues till the complete renewal of the air initially present in the drying chamber. **Fig. 15** illustrates a distributed-type solar-energy dryer with an air exit located fan [36]. It consists of an air heating unit, a vertically oriented cylindrical drying chamber and a motorized fan. Its design is quite the same with that of the wind-ventilated mixed-mode solar dryer already presented. The air heating unit is furnished with a rock bed destined for accumulating heat in order to extend its availlability even in absence of solar radiation. Air-circulation is governed by a motorized fan placed on the drying chamber. In terms of moisture evacuation from the drying chamber, humid air is driven upward and extracted under the action of the fan. This dryer has been used for drying grappes in Iran in a period where air temperature was 25°C, its relative humidity ranges from 70-85%.

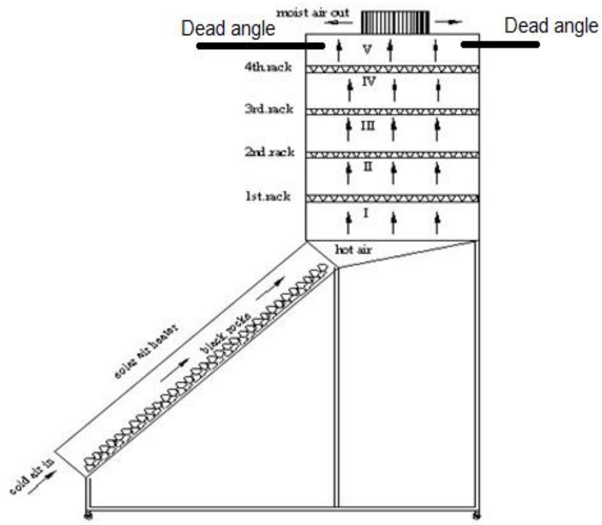

Figure 15. *Distributed solar dryer with air outlet located fans*

During the drying operations, moisture content of grappes was reduced from 81 % to 15 %. The level of grappes deterioration was recorded in the cases where drying was done with and without rock bed and the traditional sun drying method. Experiments show that the solar dryer without rock bed required 3 to 4 days to get to the final result. Grappes losses ranged from 30 to 40 %, most of them were colored red. With rock bed, the dryer required 4 to 5 days and losses ranged from 10 to 20 %. Traditionnal sun drying required 6 to 7 days with more than 50% losses recorded. This practically-designed dryer has a major drawback. Its cylindrical geometry is favourable for air mass centered on the fan. Dead angles can be identified in areas located in upper positions and not directly in the sight of the fan. **Fig. 16** illustrates a typical feature of solar-energy dryer with air-recirculation **[30]**. The recirculation arm consists of a polyethylene-tube solar collector inside which a limited volume of drying air can circulate. The polyethylene tube collector configuration consists of a black solar absorber tube inside a larger diameter clear tube acting as the glazing. In this design, air circulation is managed as follows.

Keeping air oulet closed and air inlet openned, the fan's action permits fresh air admission into the air heating unit. Secondly, without opening the air outlet air inlet is closed, the fan action forces the drying air to move according to a closed cycle.

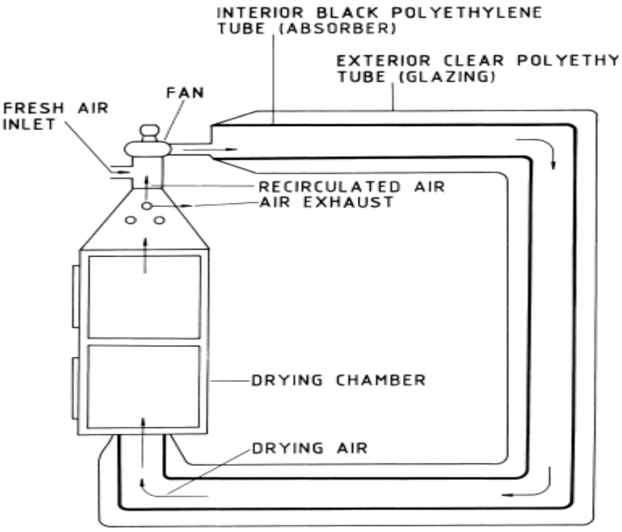

Figure 16. *Solar-energy air-recirculating dryer*

When drying air temperature is low enough, the air outlet is openned and humid air is evacuated from the drying chamber. This design permits a low exhaust air temperature and a greater efficiency. In non-recirculation drying, the drying air may still be containing some considerable moisture carrying capacity. Re-circulation of the drying air implies a higher total temperature and that the warm air is not discarded until it carries an appreciable quantity of moisture, thereby ensuring an effcient use of energy. Other practically-designed dryers availlable in the litterature are the solar collector-roof dryer and a solar collector-wall dryers. In these designs, the solar collector forms an integral part of the roof and/or wall of the drying chamber. **Fig. 17** illustrates a solar collector wall dryer [8,37]. The air heating unit consits of double layer glazing and a solar-energy absorber black wall. The air inlet is located at upper left angle of the dryer and the air oulet is a hole inside which is inserted a motorized fan at lower right angle of the dryer. A black-painted and glazed concrete wall forms the solar collector and also serves as thermal storage. Air circulation in the dryer can be described as follows. Under the action of the fan, fresh air is admited from the environment at air inlet and introduced in the air heating unit.

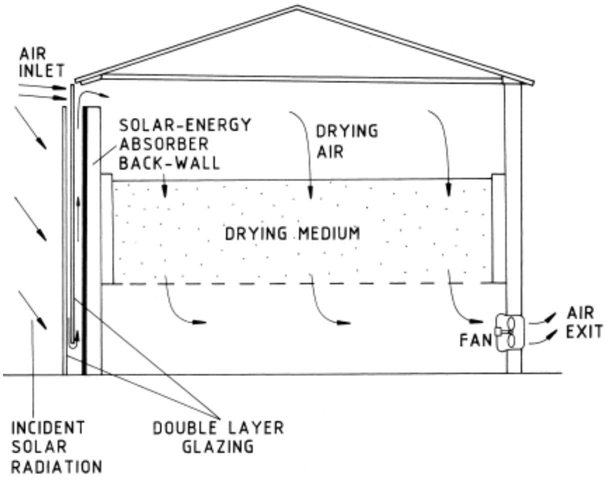

Figure 17. *A collector wall active solar-energy storage dryer*

The admited air moves downward between the double layer gazing, then upward between the interior layer glazing and the solar energy absorber black-wall. During that high speed movement, air temperature rises thereby its moisture carrying capacity increases also. The drying air enters the drying chamber from upper left side, drawn by the fan's action, it moves across the crop in the drying medium from top to bottom. During its short residency period in the drying chamber, the drying air transfers heat to the crop and carries moisture before being forced out by the fan. This practically-design has two major key forces in terms of moisture removal. First, in absence of fan's action, air distribution in the drying chamber is naturally done according to its density, humid air is less hot and moves downward because it is more dense while dry air is hotter and remains in altitude. Secondly, the naturally downward movement of moist air gets it in the nearby environment of the fan, making it availlable for immediate absorption as soon as the fan goes operationnal. This dryer has been developped and used successfully for the drying of nut crops, cereals and grains [8,37]. **Fig. 18** illustrates a solar collector-roof [8,38] dryer. In this design, parts of the wall and the roof are glazing, the permit to collect solar radiation for heating air. Air inlet is left opened and located on the lower left side of the dryer. Air exit is a hole made in the lower right side of the dryer wall inside which is located a motorized fan.

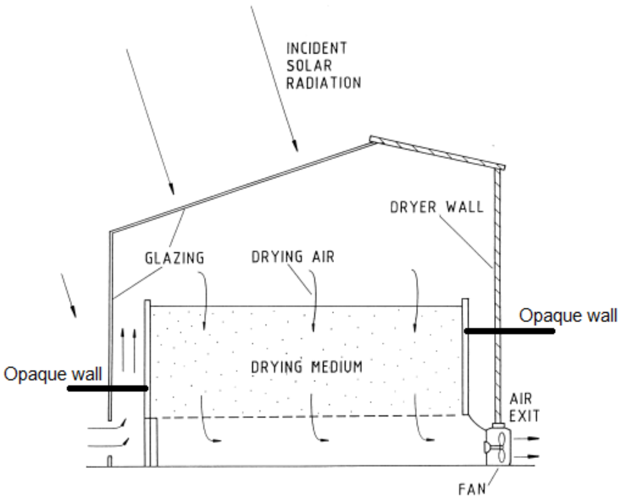

Figure 18. *A forced-convection transparent-roof solar barn*

A drying medium composed of trays supported by a frame with opaque walls is placed in the drying chamber. Under the driving force of the fan, fresh air is admited from the environment. Guided vertically by the opaque wall of the drying medium, that air moves upward in the drying chamber where it is heated. As the air moves higher than the drying medium frame, it diffuses into the hole drying chamber and continues to be heated. The air over the drying medium moves into the crop, heating it and carrying released moisture in a forced top – down movement. Once out of the drying medium, humid air is drawn out by the fan. Realised in a very efficient way, this design has the same advantages as the solar collector wall dryer and seems to present the best result since the fan placed at the level of the ground. These two designs cope very well with the conditions of small scale drying in terms of intermittent heat input, intermittent moisture extraction from the drying chamber and low drying air temperature.

3.3. Multi Fans Dryers

A particular design of dryers using many eletrically motorized fans for air circulation is proposed and studied by [5] for drying high moisture content crops from humid tropical areas.

Fig. 19 illustrates a typical feature of multi fan dryers. These dryers are constituted by a drying chamber containing, an air heater, a drying medium, three fans and an air circulation circuit.

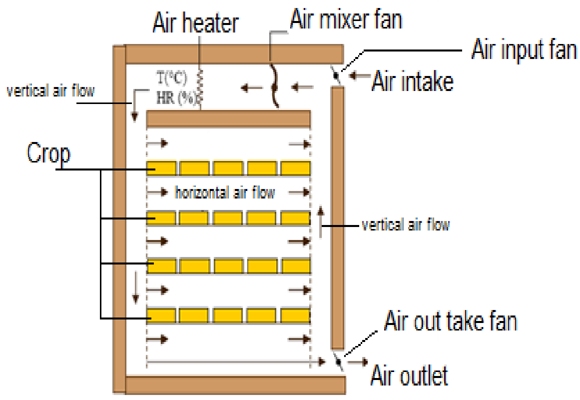

Figure 19. *Multi fan dryer*

The air heater is an electric resistance equiped with a thermometer an a hygrometer. It can be run with a high level of automatism according to drying air temperature or its moisture content. The drying medium is a metallic frame designed to support trays on which is placed the crop to dry. The drying medium stands on four supports, allowing free air circulation under the lower tray. Three fans are used for air input, air circulation in the drying chamber and air exhaust. They can be run independently or simultaneously depending on what the operator needs as result. The air circulation circuit is designed to permit free air access to every part of the drying chamber. There is a gap between the drying medium and the walls of the drying chamber to allow vertical air-circulation. There is enough space between two trays even with crop on for horizontal air flow. Air circulation in the dryer can be described in three steps: admission, moisture carrying and evacuation.

Air admission begins with air outlet closed, air inlet opened and the air intake fan on. Under the action of the air input fan, a limited fresh air is admited from the environment. It is characterized by its temperature and its moisture content. After that step, air inlet is closed, the air intake fan is put off, the internal fan and the heater go operationnal. Air temperature in the drying chamber rises progressively and willingly to the required value. In the same time, moisture carrying capacity of the drying air increases. As heat transfert from the drying air to the crop goes on, moisture is extracted and transferred from the crop to air. This step takes as long as the drying air relative humidity reaches a required value. In the las step, the internal fan and the air heater are put off, the air outlet is opened and the air out take fan is put on. A limited volume of drying is evacuated to the environment. The hole cycle is repeated until the crop is dried. Moisture evacuation is done effectively since the launching of that step depends on the drying air relative moisture value. This dryer has been succesfully tested for drying roots, fruits, cocoa and many other crops [39,40,41].

4. Moisture Removal Based on Solid Desiccant

Air dehumidification before its introduction in the drying chamber is adopted in some known drying system designs as a way of increasing moisture carrying capacity of the drying air. Heating the drying air contributes to reduce its relative humidity, this is not always possible since some crops are heat sensitive [42]. The other possibility is to reduce air moisture content thereby reducing its absolute humidity. This result can be obtained by use of liquid or solid desiccant [43]. **Fig. 20** illustrates a solar dryer equiped with an air dehumidification system using solid desiccant. The drying system consists of a solar-energy collector unit, an air dehumidification unit and a dryer. The solar-energy collector unit is composed of a water storage tank, pumps and two water/air heat exchangers located in the dehumidification unit. The solar radiation heats water in the storage tank. Hot water is sent into heat exchangers where their heat is transferred to drying air thereby increasing its temperature. The air dehumidification unit consists of two solid desiccant columns, two blowers, two water-air heat exchangers and an independent heat source. The desiccant in a column is used intermittently, adsorbsing moisture from the drying air first, being regenerated secondly. The running of the columns is also intermittent, one is used for air dehumidification while the other has its desiccant regenerated.

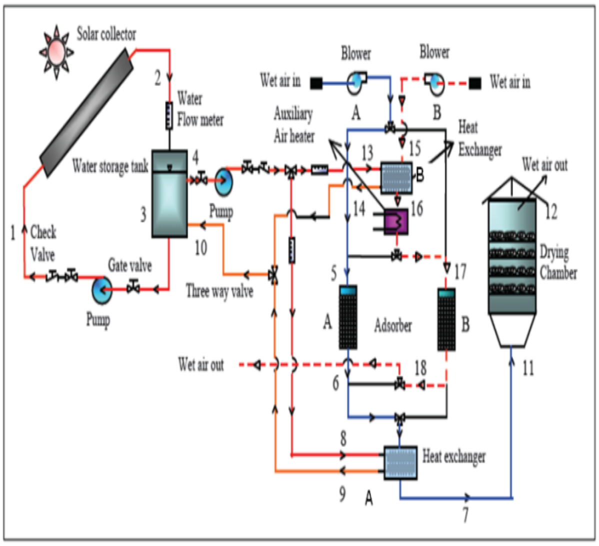

Figure 20. *Incorporation of two columns of desiccant beds into a solar drying system*

The dehumidification process is done as follows. Fresh air is admited from the environment and forced into a column containing a bed of desiccant material. During the residency period of the drying air in the column, its moisture content is partialy adsorbed by the desiccant, a first increase of the moisture carrying capacity of the drying air takes place. The dehumidified air is then heated, a second increase of the moisture carrying capacity of the drying air takes place before its introduction in the drying chamber. The regeneration process is as follows. Fresh air is admited from the environment, heated to a required value of temperature and introduced in the other column. After a residency period during which heat is transferred from the regenerating air to the desiccant and moisture is transferred from the desiccant to the air, humid air is forced out. The process continues until the desiccant is completely dried. This dryer design can be considered as a particular case of air inlet located fans admitting at its entry an air with very high moisture carrying capacity. The advantage here is that the drying air has high moisture carrying capacity even at ambient temperature, permitting the drying of heat sensitive crops [7,42]. This feature presents many drawbacks. The efficiency of the drying air decreases as drying goes on, the drying air going trhough with its absolute humidity more and more important. This situation can lead to an endless drying operation. Importance is given to the presentation of solar-energy and dehumidification units, nothing is said about the dryer itself and particulary about its drying chamber's geometry which is a very important parameter in terms of moisture removal.

5. Heat pump dryers

Tubers, vegetables and fruits consist of much water and many compounds easily modified in high temperature drying condition [44]. This results in viscous and sticky products. Conventional dryers employ large quantities of energy for heating and water removal [45]. The air exhausted from the open circuit dryer has a relatively high temperature, which is considered detrimental to the environment. A heat pump dryer is made up of five major components, namely a compressor, a condenser, an evaporator, an expansion valve. The humid air from the dryer is passed over the evaporator of the heat pump, which acts as a dehumidifier. Heat pump dryers are equiped with a fan to provide air movement. Moisture removal is therefore based on pressure gradient between air inlet and air outlet.

6. Conclusion

Our interest in this study is to see how moisture brought in by ambient air or extracted from the crop is removed from the drying chamber. Based on their moisture removal mechanism, two generic groups of dryers technology are identified. Dryers using temperature gradient to move air into and out of the drying chamber are mainly based on natural convection. In those dryers, air motion is initiated by the difference of density of the drying air particles as a consequence of air the drying air air gradient. They are mainly limited by the fact that many crops cannot withstand high temperature. Dryers using pressure gradient to move air into and out of the drying chamber are equiped with a chimney or fans/pump. Dryers equiped with chimney are based on natural convection, those provide with fans or pumps are based on forced-convection. Dryers based on natural convection are limited by the low level of Buoyancy forces they can develop. The consequence of this is that drying requires very long period of time, crops deteriorate during drying operation. Except certain designs, all dryers based on forced convection have two important limitations. First, the geometry of most drying chambers are not properly designed in order to ease the removal of humid air. Secondly, the running of fans depends on the air temperature and not on air moisture content. Drying air extraction and refreshment are coupled and governed by a single ventilation the running of wich depends on drying air temperature regardless of its moisture content. It therefore becomes impossible to follow the evolution of moisture content of drying air along the process. Exception is made in that group considering a practically-designed dryer using a specific ventilator for air intake, second one for air blowing and a third one for air outtake. Though this dryer presents more flexibility in trems of moisture removal and though it has proven its efficiency at the level of the laboratory, no study has been made in terms of dehydrating the drying chamber. A particular dryer design uses solid desiccant for moisture removal. Solid desiccant contribute to reduce moisture content of ambient air before its introduction in the heating unit. Since moisture in the chamber comes from ambient air and the crop, using desiccant to reduce air moisture content solves the problem partially. The important moisture extraction from the crop should be focused on seriously as far as humid tropical zone are concerned considering that in those areas, crops are high moisture content.

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