SOLAR DRYING

Werner Weiss

Josef Buchinger

Austrian
Development Cooperation

AEE INTEC

SOLAR DRYING

Training course within the scope of the project:

ESTABLISHMENT OF A PRODUCTION, SALES AND CONSULTING INFRASTRUCTURE

FOR

SOLAR THERMAL PLANTS

IN ZIMBABWE

Supported by the Austrian Development Cooperation

AEE INTEC

Werner Weiss
Josef Buchinger

Arbeitsgemeinschaft ERNEUERBARE ENERGIE
Institute for Sustainable Technologies
A-8200 Gleisdorf, Feldgasse 19, Austria
Tel.: +43-3112-5886, Fax: +43-3112-5886-18
E-mail: office@aee.at

AEE INTEC

Content

Abbreviations

TFNC	Tanzania Food and Nutrition Centre
EMC	equilibrium moisture content

Nomenclature

□	mass flow rate, kg/h, kg/s
□	mole fraction
ρ	air density, kg/m³
ζ	dynamic head loss coefficient
η	efficiency
λ	friction factor
ν	viscosity, m²/s
A	area, m²
A_C	collector reference area (normally: aperture area), m²
a_w	water activity
c	air velocity, m/s
c_P	specific heat, J/kg/K
d	diameter, m
G	solar global irradiance, W/m²
L	latent heat of water, 2257 kJ/kg @ 1,013225 bar
l	length, m
m	mass, kg
Q	heat energy, J
Q	heat flux, W
RH	relative humidity, %
T	Temperature, °C, K
t	time, s
V $\dot{V}$	air flow rate, m³/h
x	moisture content, %wb, kg water/kg wet solids
X	moisture, %db, kg water/kg dry solids
X^A	absolute humidity of air, kg water/kg dry air,
db	dry bulb
wb	wet basis

Indexes

A	air
a	ambient
C	crop
D	dry
e	equlibrium
f	final
i	inlet, initial
o	outlet
W	wet
w	water

1 Introduction

In the majority of African countries, agriculture represents the biggest part of the economy. 80-90% of the working population is employed in agriculture. Despite these large numbers, national food production still does not meet the needs of the population. The lack of appropriate preservation and storage systems caused considerable losses, thus reducing the food supply significantly.
The dent in food production caused by crop-failures as well as significant seasonal fluctuations in availability can be ironed out by food conservation, e.g., by drying.

Sun drying of crops is the most widespread method of food preservation in a lot of African countries due solar irradiance being very high for the most of the year. There are some drawbacks relating to the traditional method of drying, i.e., spreading the crop in thin layers on mats, trays or paved grounds and exposing the product to the sun and wind.
These include poorer quality of food caused by contamination by dust, insect attack, enzymatic reactions and infection by micro-organisms.
Also this system is labour- and time intensive, as crops have to be covered at night and during bad weather, and the crops continually have to be protected from attack by domestic animals.
Non-uniform and insufficient drying also leads to deterioration of the crop during storage.
Serious drying problems occur especially in humid tropical regions where some crops have to be dried during the rainy season.

Fig. 1: Traditional sun drying of sweet pepper (left) and coffee (right) in Zimbabwe

In order to ensure continuous food supply to the growing population and to enable the farmers to produce high quality marketable products, efficient and at the same time affordable drying methods are necessary. Studies have shown that even small and most simple oil-fired batch dryers are not applicable for the most farmers, due to lack of capital and insufficient supply of energy for the operation of the dryers.

The high temperature dryers used in industrialised countries are found to be economically viable in developing countries only on large plantations or big commercial establishments [1].
Therefore the introduction of low cost and locally manufactured solar dryers offers a promising alternative to reduce the tremendous post harvest losses. The opportunity to produce high quality marketable products seems to be a chance to improve the economic situation of the farmers. However, taking into account the low income of the rural population in developing countries, the relatively high initial investment for solar dryers still remains a barrier to a wide application.

2 Solar radiation – the energy source for solar drying

The sun is the central energy producer of our solar system. It has the form of a ball and nuclear fusion take place continuously in its centre. A small fraction of the energy produced in the sun hits the earth and makes life possible on our planet. Solar radiation drives all natural cycles and processes such as rain, wind, photosynthesis, ocean currents and several other which are important for life. The whole world energy need has been based from the very beginning on solar energy. All fossil fuels (oil, gas, coal) are converted solar energy.

The radiation intensity of the ca 6000°C solar surface corresponds to 70,000 to 80,000 kW/m2. Our planet receives only a very small portion of this energy. In spite of this, the incoming solar radiation energy in a year is some 200,000,000 billion kWh; this is more than 10,000 times the yearly energy need of the whole world.

The solar radiation intensity outside the atmosphere is in average 1,360 W/m^2 (solar constant). When the solar radiation penetrates through the atmosphere some of the radiation is lost so that on a clear sky sunny day in summer between 800 to 1000 W/m^2 (global radiation) can be obtained on the ground.

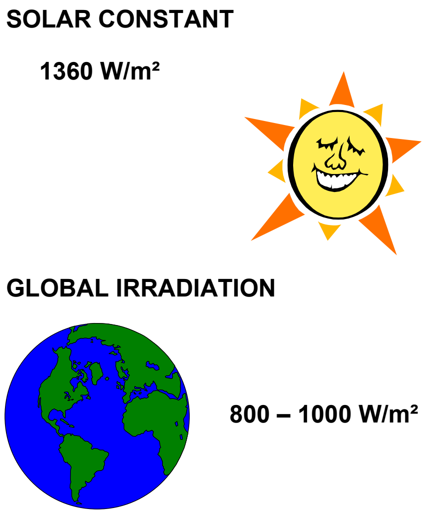


Fig. 2: Solar constant and global irradiation

2.1 Global radiation

The duration of the sunshine as well as its intensity is dependent on the time of the year, weather conditions and naturally also on the geographical location. The amount of yearly global radiation on a horizontal surface may thus reach in the sun belt regions over 2,200 kWh/m^2. In north Europe, the maximum values are 1,100 kWh/m^2.

The global radiation composes of direct and diffuse radiation. The direct solar radiation is the component which comes from the direction of the sun. The diffuse radiation component is created when the direct solar rays are scattered from the different molecules and particles in the atmosphere into all directions, i.e. the radiation becomes unbeamed. The amount of diffuse radiation is dependent on the climatic and geographic conditions. The global radiation and the proportion of diffuse radiation is greatly influenced by clouds, the condition of the atmosphere (e.g. haze and dust layers over large cities) and the path length of the beams through the atmosphere.

Table 1: Global irradiance and diffuse fraction, depending on the cloud conditions

	Clear, blue sky	Scattered clouds	Overcast sky
Solar irradiance [W/m²]	600 - 1000	200 – 400	50 - 150
Diffuse fraction [%]	10 - 20	20 – 80	80 - 100

The higher the amount of diffuse radiation is, the lower is the energy contents of the global solar radiation. The monthly and annual averages of daily radiation (kWh/m^2, day) for selected locations are shown in Table 2.

Table 2: Average monthly and yearly values of global solar radiation on a horizontal surface in kWh/m².

	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Year	Lat
EUROPE														
London, GB	17	31	64.2	91.1	128.0	150	136	112	81.3	48.3	24	15	**767**	51.5 N
Vienna, Austria	25.2	43	81.4	118.9	149.8	160.7	164.9	139.7	100.6	59.8	26.3	19.9	**1090**	48.2 N
AFRICA														
Kampala, Ug.	174	163.9	170.4	153.4	151.0	142.6	141.4	151.0	154.8	163.7	154.0	164.4	**1885**	0.5 S
Moshi, Tanzania	179.8	169.4	179.8	162.0	148.8	148.8	147.2	187.6	169.5	182.9	165.0	178.2	**2019**	5.0 S
Harare, Zim.	175.1	147.8	163.2	152.0	145.7	135.1	145.8	165.3	178.2	190.3	172.2	172.3	**1943**	17.5 S

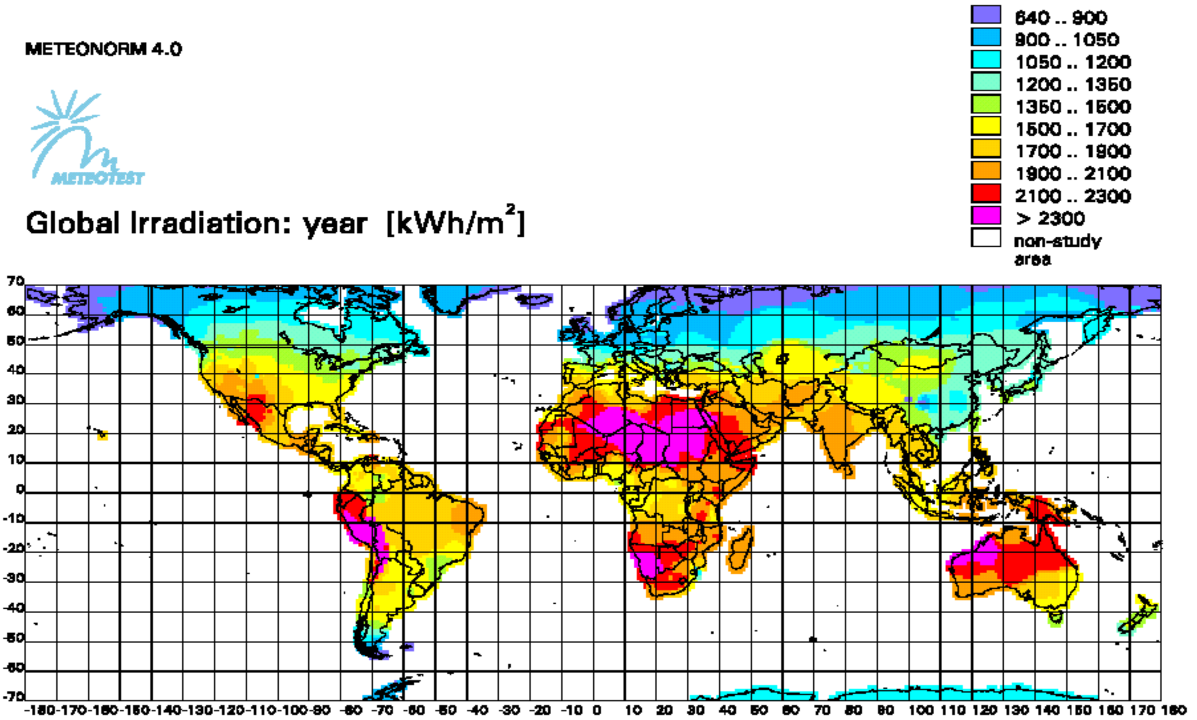


Fig. 3: Yearly average sums of global irradiation

Depending on the geographic location the yearly global radiation on a horizontal surface may vary between 1000 (Europe) and 2200 kWh/m2 (Africa).

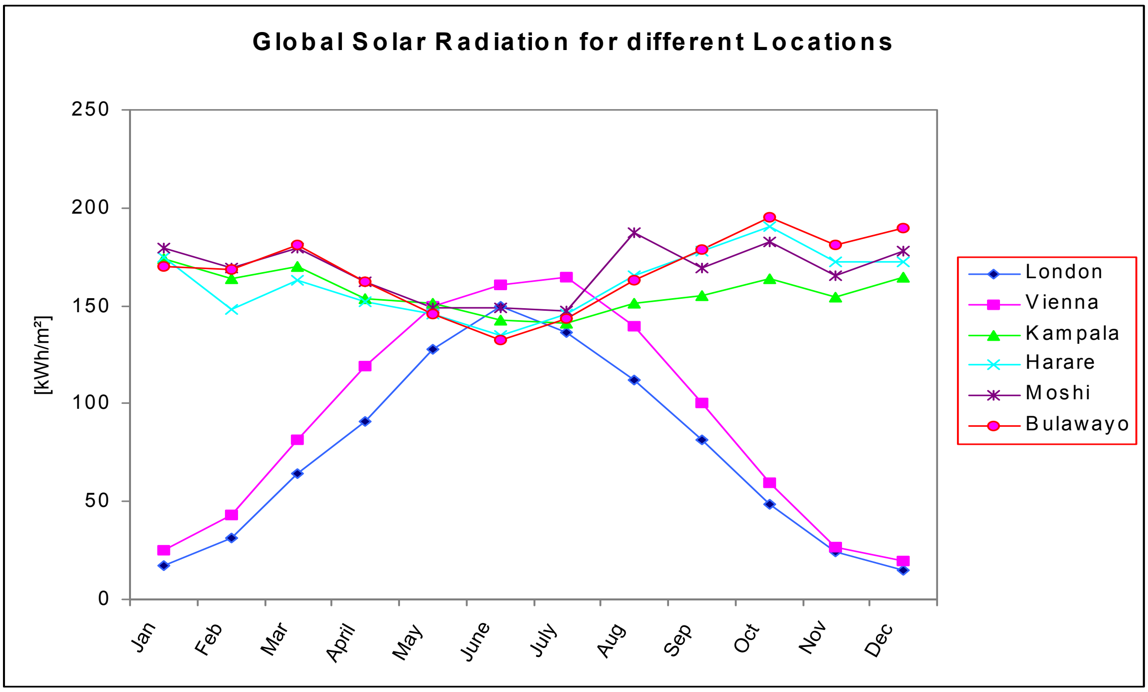


Fig. 4: Average monthly values of global solar radiation on a horizontal surface

3 Sun drying versus solar drying

Solar drying is a possible replacement for sun drying or for standard dehydration processes. In terms of sun drying, solar drying is competing with an approach that is deeply entrenched in the way of life for most potential users. Sun drying is by no means a perfect process with problems arising due to potential contamination of the produce, variability in drying times, rain damage and so on. However some of the reasons proposed for the lack of success in adoption of solar drying are as follows:

- Solar dryers have often been too expensive or initial investment capital or loan facilities were unavailable.
- Solar dryers have often been too complicated or poor training of local entrepreneurs and technicians was provided.
- Solar dryers have often required too big changes from traditional methods.
- Solar dryers have not been built for long term use.
- There is a lack of incentive to improve the quality of the product. People are willing to pay nearly the same amount for discoloured or damaged foods and there is therefore no incentive for producers to risk higher amounts of money in a dryer when there is not a great return.

When comparing solar drying to the conventional dehydration processes a new range of issues arises. These include:

- Solar dryers must provide the equivalent performance to that of the conventional processes in terms of capacity, labour input, the quality of the final product, the total drying costs and reliability.
- A backup heating system should be installed to ensure drying during the critical periods when the weather is bad.

Advantages of solar drying can be summarized as follows:

- The higher temperature, movement of the air and lower humidity, increases the rate of drying.
- Food is enclosed in the dryer and therefore protected from dust, insects, birds and animals.
- The higher temperature deters insects and the faster drying rate reduces the risk of spoilage by micro organisms.
- The higher drying rate also gives a higher throughput of food and hence a smaller drying area (roughly 1/3).
- The dryers are water proof and the food does not therefore need to be moved when it rains.
- Dryers can be constructed from locally available materials and are relatively low cost.
- More complete drying allows longer storage

3.1.1 Processes during sun drying

Exposing agricultural products to wind and sun is the preservation method practiced over centuries throughout the world. Cereals, legumes and green forages are dried in the field immediately after harvesting. Fruits, vegetables, spices and marine products as well as threshed grains are spread out in thin layers on the ground or trays, respectively. Other methods include hanging the crop underneath a shelter, on trees or on racks in the field.

For better understanding of the processes during solar drying, the process of sun drying is described in first.

During sun drying heat is transferred by convection from the surrounding air and by absorption of direct and diffuse radiation on the surface of the crop. The converted heat is partly conducted to the interior increasing the temperature of the crop and partly used for effecting migration of water and vapour from the interior to the surface. The remaining amount of energy is used for evaporation of the water at the surface or lost to ambient via convection and radiation. The evaporated water has to be removed from the surrounding of the crop by natural convection supported by wind forces. [1]

Under ambient conditions, these processes continue until the vapour pressure of the moisture held in the product equals that held in the atmosphere. Thus, the rate of moisture desorption from the product to the environment and absorption from the environment are in equilibrium, and the crop moisture content at this condition is known as the equilibrium moisture content. Under ambient conditions, the drying process is slow, and in environments of high relative humidity, the equilibrium moisture content is insufficiently low for safe storage [6].

Fig. 5 and Fig. 6 show a schematic diagram of heat and mass transfer processes influencing sun drying.

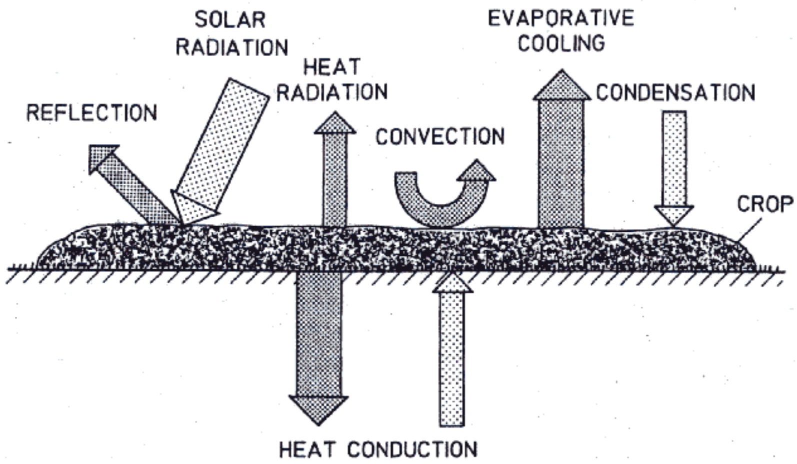


Fig. 5: Heat flow influencing sun drying [7]

Due to the hygroscopic properties of all agricultural products, during sun drying the crop can either be dried or rewetted. Especially during night time when ambient temperature in general is decreasing, causing a simultaneous increase of the humidity, remoistening effects can occur either by condensation of dew or by vapour diffusion caused by osmotic or capillary forces.

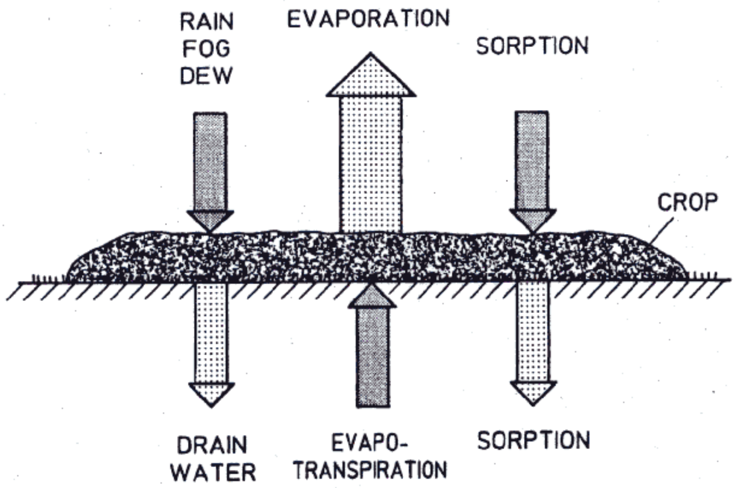


Fig. 6: Mass flow influencing sun drying [7]

As described above this method of drying has a lot of disadvantages. A technical alternative to the traditional method of sun drying is solar drying.

3.1.2 Processes during solar drying

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 significantly the relative humidity of the drying air and thereby increasing its moisture carrying capacity and ensuring sufficiently low equilibrium moisture content.[6]

One type of solar dryer is shown in Fig. 7. It was designed for the particular requirements of rice but the principles hold for other products and design types, since the basic need to remove water is the same.

Air is drawn through the dryer by natural convection. It is heated as it passes through the collector and then partially cooled as it picks up moisture from the rice. The rice is heated both by the air and directly by the sun.

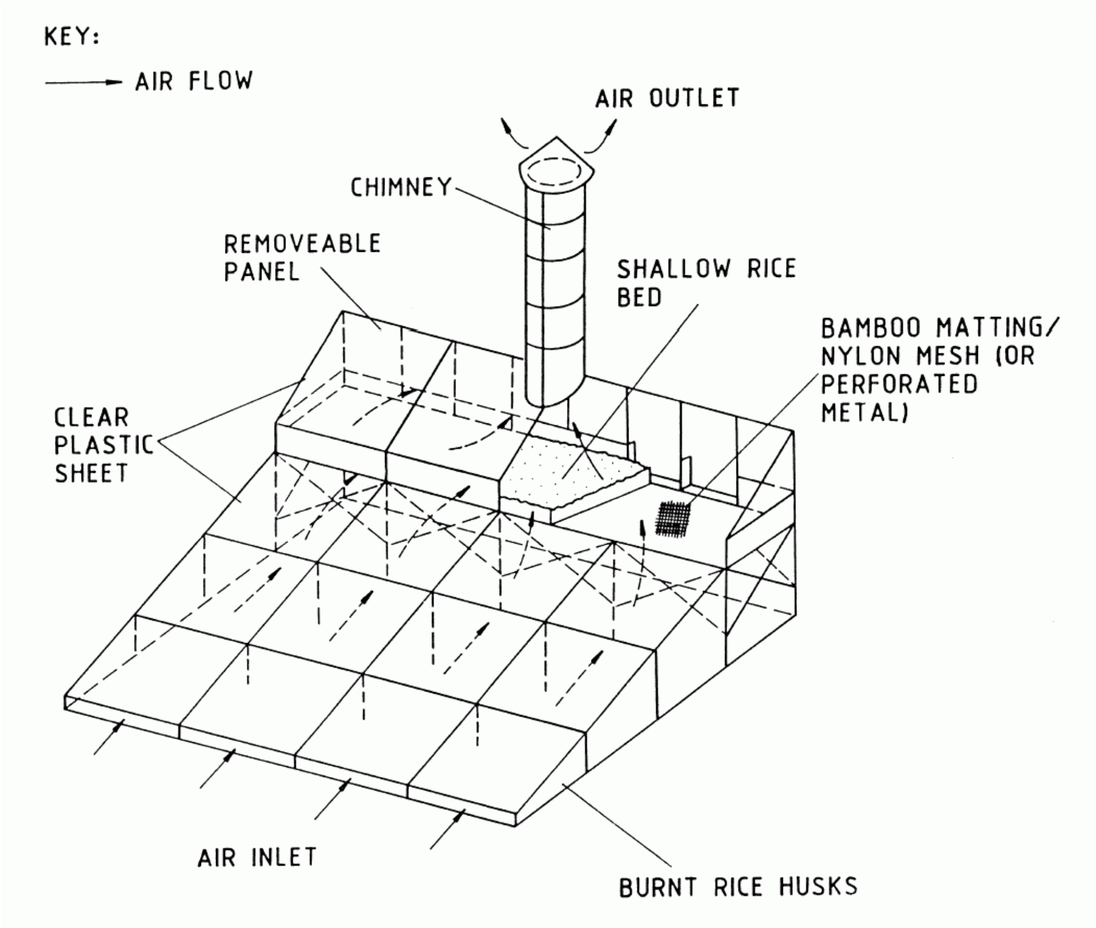


Fig. 7: Solar rice dryer [6]

Warm air can hold more moisture than cold air, so the amount required depends on the temperature to which it is heated in the collector as well as the amount held (absolute humidity) when it entered the collector. The way in which the moisture absorption capability of air is affected by its initial humidity and by the temperature to which it is subsequently heated is shown in Table 3.

Table 3: The drying process (air enters at 20 °C and leaves at 80% RH) [8].

Initial relative humidity	**Moisture absorption capability (grams of water per m³ of air [g/m³])**		
	Not heated	Heated to 40 °C	Heated to 60 °C
40 %	4,3	9,2	16,3
60 %	1,4	8,2	15,6
80 %	0	7,1	14,9

The objective of most drying processes is to reduce the moisture content of the product to a specified value. Moisture content (wet basis) is expressed as the weight of water as a proportion of total weight (see Appendix A for initial moisture content of different crops). The moisture content of rice has typically to be reduced from 24 % to 14 %. So to dry one tonne of rice, 100 kg of water must be removed.

If the heated air has a 'absorption capacity' of 8 g/m^3 then 100/0.0008 = 12,500 m^3 of air are required to dry one tonne of rice.

The heat required to evaporate water is 2.26 kJ/kg. Hence, approximately 250 MJ (70 kWh) of energy are required to vaporise the 100 kg water. There is no fixed requirement for solar heat input to the dryer. This is because the incoming ambient air can give up some of its internal energy to vaporise the water (becoming colder in the process). Indeed, if the ambient air is dry enough, no heat input is essential.

Nevertheless, extra heat is useful for two reasons. First, if the air is warmer then less of it is needed. Second, the temperature in the rice grains themselves may be an important factor, especially in the later stages of drying, when moisture has to be 'drawn' from the centres of the grains to their surfaces. This temperature will itself depend mainly on the air temperature but also on the amount of solar radiation received directly by the rice.

Numerous types of solar dryers were developed to reduce post harvest losses and to improve the product quality. In the following they are classified and some of them are described.

4 Classification of solar dryers

All drying systems can be classified primarily according to their operating temperature ranges into two main groups of high temperature dryers and low temperature dryers. However, dryers are more commonly classified broadly according to their heating sources into fossil fuel dryers (more commonly known as conventional dryers) and solar-energy dryers. Strictly, all practically-realised designs of high temperature dryers are fossil fuel powered, while the low temperature dryers are either fossil fuel or solar-energy based systems.

To classify the various types of solar dryers, it is necessary to simplify the complex constructions and various modes of operation to the basic principles. Solar dryers can be classified based on the following criteria:

- Mode of air movement
- Exposure to insulation
- Direction of air flow
- Arrangement of the dryer
- Status of solar contribution

Following Ekechukwu [9], solar dryers can be classified primarily according to their heating modes and the manner in which the solar heat is utilised. In broad terms, they can be classified into two major groups, namely:

1. active solar-energy drying systems (most types of which are often termed hybrid solar dryers); and
2. passive solar-energy drying systems (conventionally termed natural-circulation solar drying systems).

Three distinct sub-classes of either the active or passive solar drying systems can be identified (which vary mainly in the design arrangement of system components and the mode of utilisation of the solar heat, namely [9]:

- integral-type solar dryers;
- distributed-type solar dryers; and
- mixed-mode solar dryers.

The main features of typical designs of the various classes of solar-energy dryers are illustrated in Fig. 8.

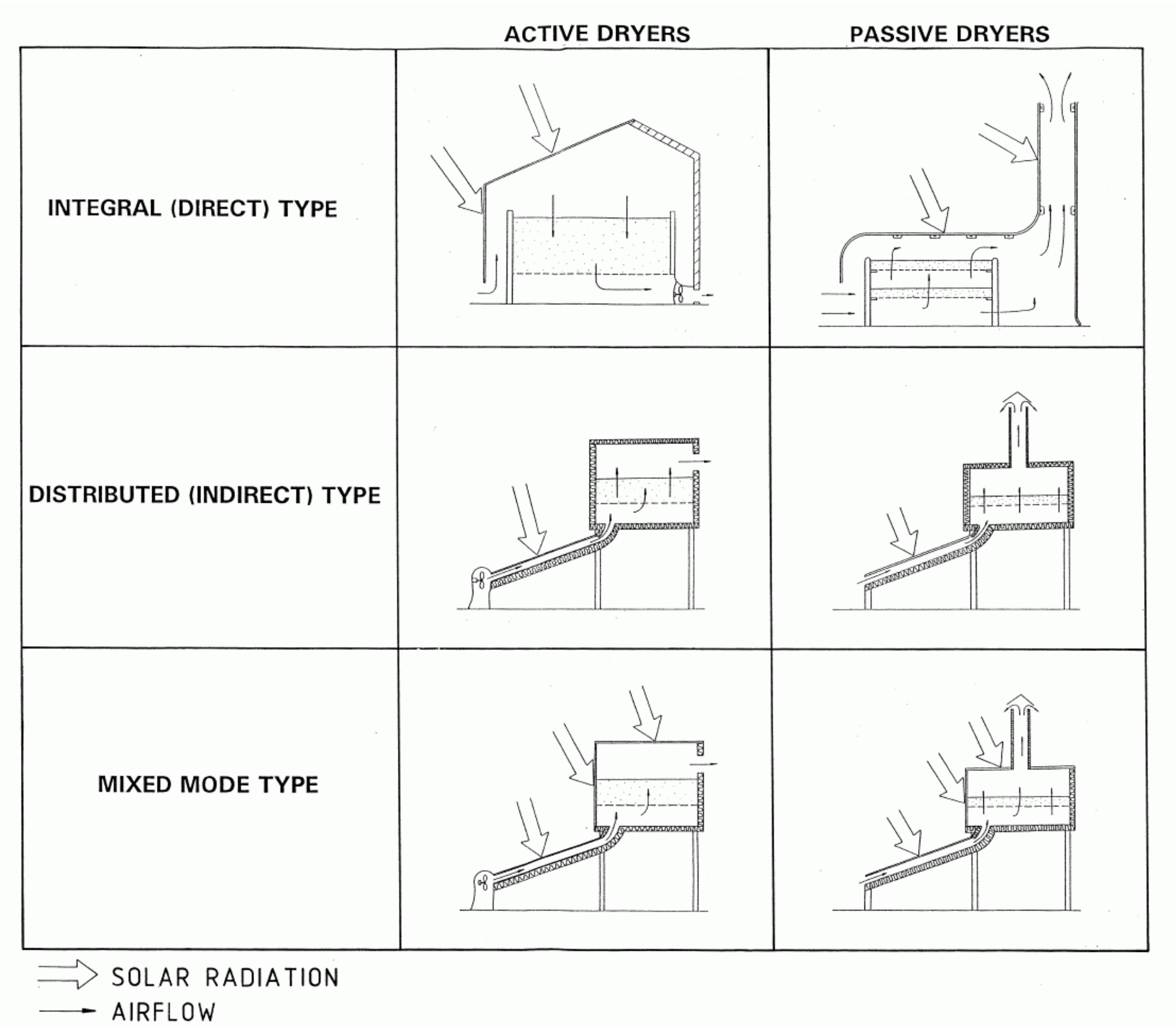


Fig. 8: Classification of solar dryers. [6]

Natural convection is used on the diminution of the specific weight of the air due to heating and vapour uptake. The difference in specific weight between the drying air and the ambient air promotes a vertical air flow. Natural convection dryers therefore can be used independent from electricity supply. However, the airflow in this type of dryer is not sufficient to penetrate higher crop bulks. Furthermore the air flow comes to a standstill during night and adverse weather conditions. The risk of product deterioration due to mould attack and enzymatic reactions is high.

Furthermore the mode of drying can be differentiated into direct and indirect, depending whether the product is directly exposed to solar radiation or dried in the shade. In direct mode, the product itself serves as absorber, i.e. the heat transfer is affected not only by convection but also by radiation according to the albedo of the product surface. Therefore, the surface area of the product being dried has to be maximized by spreading the crop in thin layers. To obtain uniform final moisture content, the crop has to be turned frequently.

Using integral (direct) mode of drying, is should be noted, that sunlight may affect certain essential components in the product e.g. chlorophyll is quickly decomposed. Due to the limitation of the bulk depth, such dryers need large ground surface areas. If grounds are scarce, indirect mode type of dryers are preferred for drying larger quantities.

4.1 Passive solar dryers

Passive solar dryers are also called natural circulation or natural convection systems. They are generally of a size appropriate for on-farm use. They can be either direct (e.g. tent and box dryer) or indirect (e.g. cabinet dryer). Natural-circulation solar dryers depend for their operation entirely on solar-energy. In such systems, solar-heated air is circulated through the crop by buoyancy forces or as a result of wind pressure, acting either singly or in combination.

4.1.1 Tent dryers

Tent solar dryers, as shown in Fig. 9, are cheap and simple to build and consist of a frame of wood poles covered with plastic sheet. Black plastic should be used on the wall facing away from the sun. The food to be dried is placed on a rack above the ground. Drying times are however not always much lower than for open-air drying (-25 %). (Probably, insufficient attention has so far been paid to utilizing natural convection.) The main purpose of the dryers may be to provide protection from dust, dirt, rain, wind or predators and they are usually used for fruit, fish, coffee or other products for which wastage is otherwise high. Tent dryers can also be taken down and stored when not in use. They have the disadvantage of being easily damaged by strong winds.

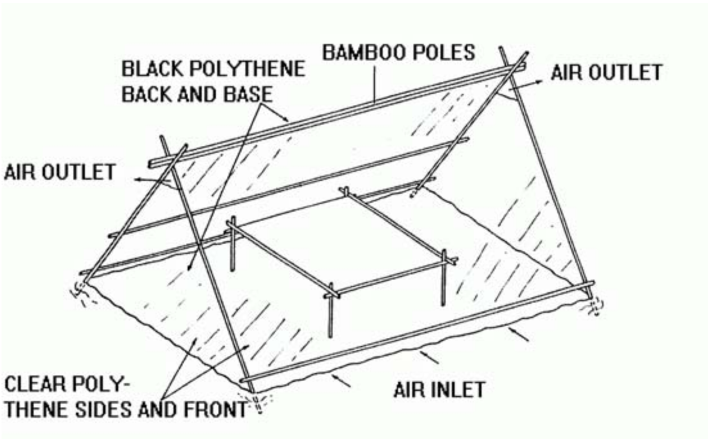


Fig. 9: Solar tent dryer [3] left, DTC, University of Zimbabwe, right

4.1.2 Box dryers

The box-type solar dryer has been widely used for small scale food drying. It consists of a wooden box with a hinged transparent lid. The inside is painted black and the food supported on a mesh tray above the dryer floor. Air flows into the chamber through holes in the front and exits from vents at the top of the back wall.
Pioneering works on solar cabinet dryers were reported by the Brace Research Institute, Canada. Fig. 10 illustrates the fundamental features of the standard Brace Institute solar cabinet dryer. Brace type dryers achieve higher temperatures, and thus shorter drying times, than tent dryers. Drying temperatures in excess of about 80 °C were reported for the dryer.[6]

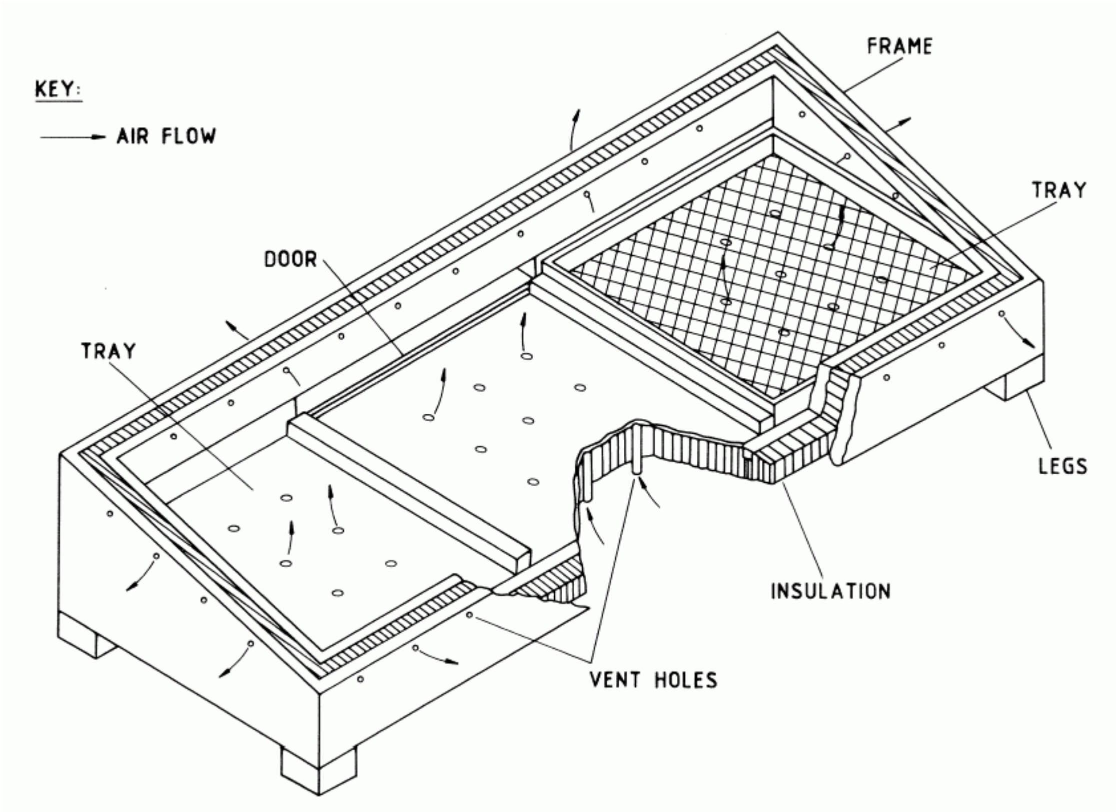


Fig. 10: Box dryer [6]

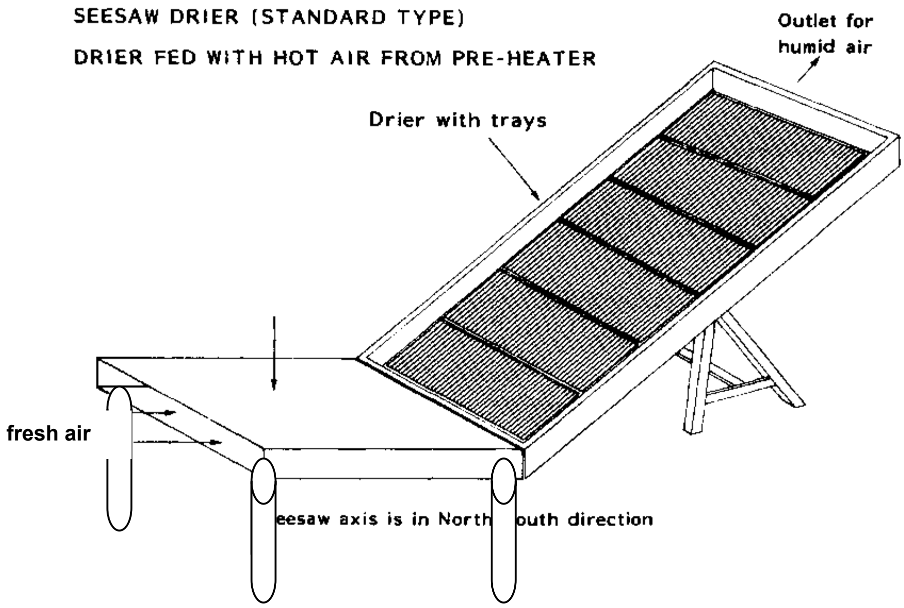
4.1.3 Seesaw dryer

The traditional seesaw dryer [10] has a rigid, rectangular frame, the length of which being 3 times the width' resting on a support with an axis. This support is oriented north-south and is sufficiently high to allow the frame to be tilted 30° - towards east in the morning and towards west in the afternoon.

The material for drying is placed on a number of trays, which have a wooden frame 100 x 50 cm and a mesh bottom, which can be made of a variety of materials, such as wire netting, old fishing nets, bamboo lattice or any other material that will allow vertical air circulation and maximum evaporation.

The bottom of the improved seesaw dryer is made of galvanised corrugated iron sheets reinforced crosswise by wooden planks and lengthwise by two wooden planks, about 15 cm high. The upper surface of the bottom is painted black. Good thermal insulation can be provided by attaching insulation plates made of lignified wood fibre, expanded polystyrene various layers of corrugated cardboard etc. to the underside of the bottom.

The removable trays are placed on top of the corrugated iron bottom either in a continuous row or with space between them, which will result in better heating of the air above the blackened surface of the corrugated iron bottom. In this case the edges of the trays should be propped up with wooden supports.



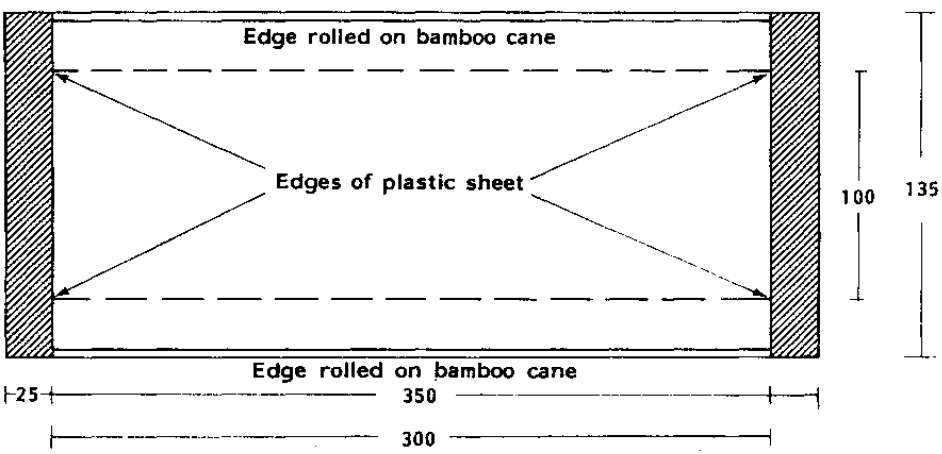


Fig. 11: Seesaw dryer [10]

Fig. 12: Seesaw dryer at the DTC, University of Zimbabwe

A greenhouse effect is obtained by placing a transparent plastic sheet over the filled trays. This sheet rests on the raised edges of the trays and is kept stretched by the weight of bamboo canes fixed to the sides of the plastic sheet. When not in use the sheet is rolled around the bamboo canes.

Air circulation is secured by convection, the dryer being tilted at an angle of 30°: fresh air enters at the lower end of the chamber formed by the trays and the plastic covering' escaping at the upper end. A 3 m long dryer tilted 30° has 1.40 m difference in levels of air inlet and air outlet.

Air circulation can be improved still more by making the air outlet opening wider (28 x 50 cm) than the air inlet opening (15 x 50). In this way the room enclosed by the dryer bottom and the plastic sheet widens gradually from air inlet to air outlet. This will improve convection and prevent the formation of "hot air bubbles" inside caused by air dilatation.

4.1.4 Cabinet solar dryers

Here, the crop is located in trays or shelves inside a drying chamber. If the chamber is transparent, the dryer is termed an integral-type or direct solar dryer. If the chamber is opaque, the dryer is termed distributed-type or indirect solar dryer Fig. 13. Mixed-mode dryers combine the features of the integral (direct) type and the distributed (indirect) type solar dryers. Here the combined action of solar radiation incident directly on the product to be dried and pre-heated in a solar air heater furnishes the necessary heat required for the drying process.

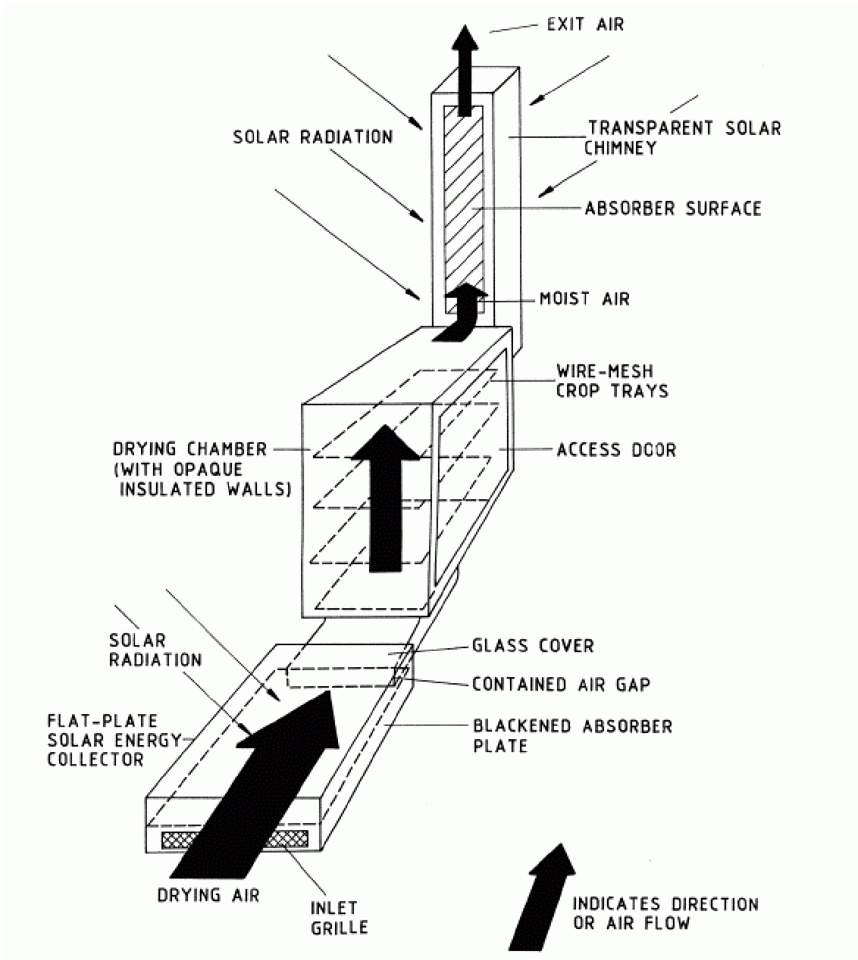


Fig. 13: Features of a typical distributed (indirect) mode natural convection cabinet dryer. [6]

In most cases the air is warmed during its flow through a low pressure drop thermosyphonic solar collector and passes through air ducts into the drying chamber and over drying trays containing the crops. The moist air is then discharged through air vents or a chimney at the top of the chamber.

The cabinet is a large wooden or metal box. It should be insulated properly to minimise heat losses and made durable (within economically justifiable limits). Construction from metal sheets or water resistant cladding, e.g. paint or resin, is recommended.

Inside the box internal runners are fitted to support the trays of food being processed. A general rule of thumb is that one m² of tray area is needed to lay out 10 kg of fresh produce [11]. Access to the inside of the dryer is via hinged doors at the rear of the cabinet. The drying trays slide on rails on the inside of the cabinet so that they can be removed from the dryer for loading, unloading and cleaning.

Fig. 14: Loading of a cabinet dryer (Harare, Zimbabwe)

Heated air flows through the stack of trays until the entire product is dry. Clearly, as the hot air enters below the bottom tray, this tray will dry first. The last tray to dry is the one at the top of the chamber. The advantages and disadvantages of this system are:

- \+ simple chamber
- \+ low labour costs – simply load and then unload
- \+ the food need not be exposed to the direct rays of the sun which reduces the loss of colour and vitamins.
- \+ heat storage systems can be applied
- − a tendency to over-dry the lower trays
- − low efficiency, in terms of fuel consumption, in the later stages of drying when most of the trays are dry.

Further major drawbacks for natural convection solar dryers are the poor moist air removal which reduces drying rate and the very high internal temperatures with the likelihood of over heating the product. Drying air temperatures as high as 70 °C - 100 °C may be reached with these dryers. These temperatures are excessive for most products. The most severe constraints are on beans (35°C), rice (45°C), and all grains if they are to be used for seed (45°C).

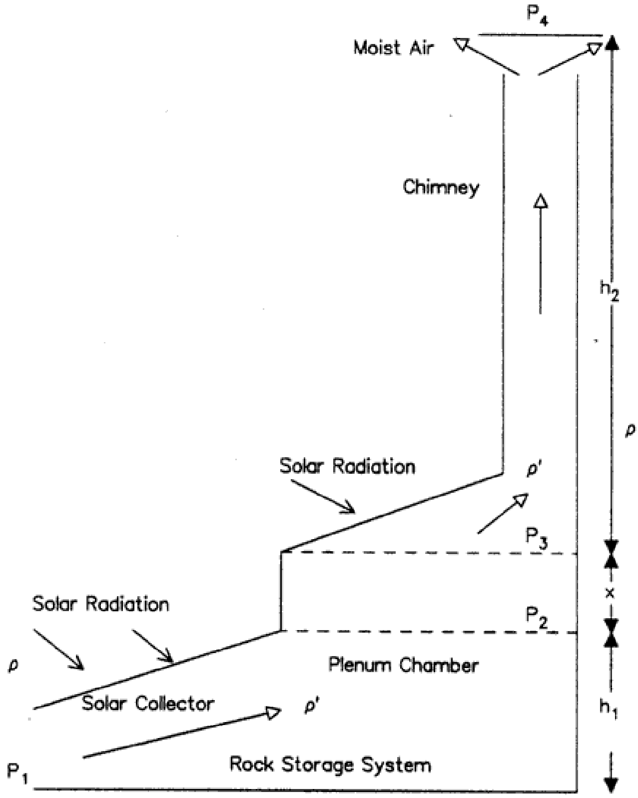


Fig. 15: Solar cabinet dryer with natural convection

In a natural convection system, the flow of air is caused by the fact that the warm air inside the dryer is lighter than the cooler air outside. This difference in density creates a small pressure difference across the bed of grain, which forces the air through it. This effect increases the higher the height of the bed is above the inlet (h1 in Fig. 15) and the outlet above the bed (h2). The effect of an increased h2 is less than that of an increased h1 because the air is cooled as it passes through the bed.

Table 4: Air density variation in a natural convection dryer (Air enters at 20°C and leaves at 80% RH)

Initial relative humidity	Density of the air (kg/m^3) (Drop in density, in brackets)			
	Not heated		Heated to	
		30 °C	40 °C	60 °C
40%	Ambient 1.19	1.19	1.19	1.19
	Below bed 1.19 (.00)	1.15 (.04)	1.12 (.07)	1.05 (.14)
	Above bed 1.21 (-.02)	1.19 (.00)	1.17 (.02)	1.14 (.05)
60%	Ambient 1.19	1.19	1.19	1.19
	Below bed 1.19 (.00)	1.15 (.04)	1.11 (.08)	1.05 (.14)
	Above bed 1.20 (-.01)	1.18 (.01)	1.16 (.03)	1.13 (.06)
80%	Ambient 1.18	1.18	.18	1.18
	Below bed 1.18 (.00)	1.14 (.04)	1.11 (.07)	1.04 (.14)
	Above bed 1.18 (.00)	1.16 (.02)	1.15 (.03)	1.11 (.07)

It can be seen in Table 4 that if the incoming air is heated by only 10-30°C then the presence of a chimney on top of the dryer would make little or no difference, unless it acted efficiently as a solar collector and raised the temperature of the air significantly. So a solar chimney increases the buoyancy force imposed on the air stream and provides a higher air flow velocity and, thus, a more rapid rate of moisture removal.

It should be noted that even if the difference in densities is as much as 0.5 kg/m³, then the resulting pressure difference is only 0.5 Pa (5 millionths of atmospheric pressure) per metre of chimney. For comparison, forced convection systems commonly operate with pressure differences of 100-500 Pa.

One of the earliest designs to enhance ventilation in cabinet solar dryers is the solar and wind-ventilated dryer, illustrated in Fig. 16 (left). The design uses a ventilator which depends entirely on the wind effect. Air is drawn through the dryer by wind-powered rotary vanes located on top of the dryer chimney. Temperature and air flow rates are controlled by a damper.

Fig. 16: Passive cabinet solar dryers in Zimbabwe (Domestic Solar Heating left, DTC, UZ, right)

The rotary wind ventilator, made of a moving corrugated vane rotor, is placed on top of a stack above the drying chamber. The stack requires an appropriate length to achieve a chimney effect and catch more wind. As the rotor spins in the wind, it expels air from the ventilator stack. The rotor is mounted on a ball bearing suspension with low friction.
Monitoring results of rotary wind ventilators installed on cabinet dryers in Zimbabwe showed low performance, because its limitation is that it can only follow the wind pattern and is essentially inoperative between wind peaks and has periods of complete inactivity during lulls. Air flows are critical factors in natural-circulation solar drying, thus they should be used especially in areas with relatively high average wind speed.

Modifications to the typical cabinet dryer designs include absorbers equipped with thermal storage, either of a rock bed [13] or water.

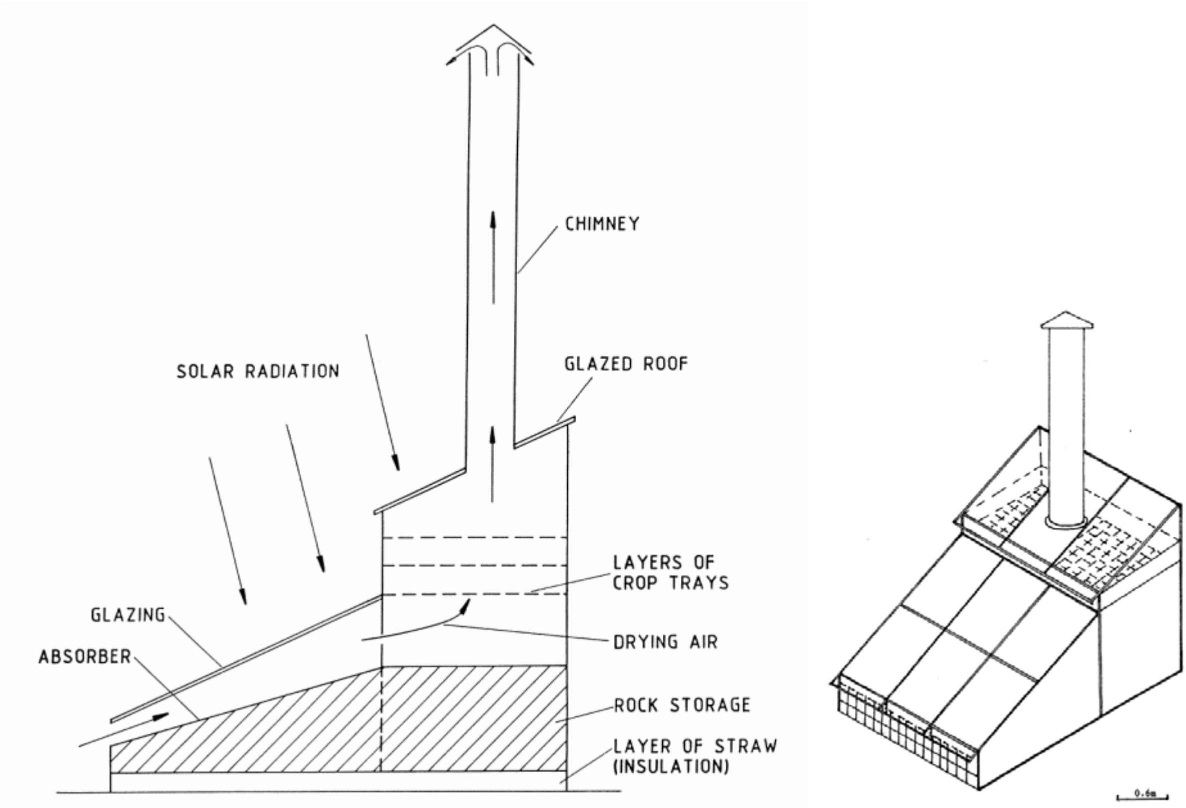


Fig. 17: Schematic diagram of fixed bed dryer with a rock storage system.[6, 13]

4.2 Active solar cabinet dryers

Active solar dryers are also called forced convection or hybrid solar dryers. Optimum air flow can be provided in the dryer throughout the drying process to control temperature and moisture in wide ranges independent of the weather conditions. Furthermore the bulk depth is less restricted and the air flow rate can be controlled. Hence, the capacity and the reliability of the dryers are increased considerably compared to natural convection dryers.

It is generally agreed that well designed forced-convection distributed solar dryers are more effective and more controllable than the natural-circulation types.

The use of forced convection can reduce drying time by three times and decrease the required collector area by 50 %. Consequently, dryer using fans may achieve the same throughput as a natural convection dryer with a collector six times as large [19]. Fans may be powered with utility electricity if it is available, or with a solar photovoltaic panel.
Almost all types of natural convection dryers can be operated by forced convection as well.

4.2.1 Active ventilated cabinet solar dryers

If utility electricity is available it is cheaper to connect the fans to the grid, compared to a connection to a PV installation. Besides the fans also an electronic controller may be connected to the grid, which is able to adjust the appropriate temperature by variable speed of the fan.

Fig. 18: Active ventilated cabinet dryer with fan on the top (Harare, Zimbabwe)

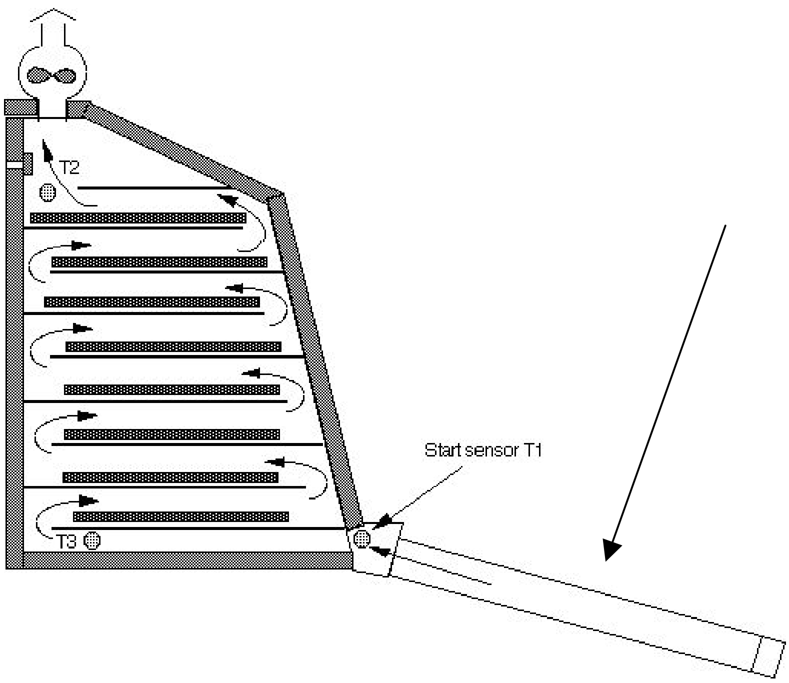


Fig. 19: Cross section of the active ventilated cabinet dryer. Three temperature sensors control the temperature inside the cabinet. The temperature is adjusted to the respective fruit by a variable speed controlled fan.

In a **PV-powered system**, the fan is directly coupled to the solar module, working without an accumulator and load controller. Increasing solar radiation increases the module's output, thus speeding up the fan. This has the advantage of permitting a simple temperature control merely by appropriately designing the components of the PV system, thus obviating any additional control devices as long as the system is suitably dimensioned.

Fig. 20: PV-powered solar vegetable and fruit dryer (Zimbabwe)

Fig. 21: The fan is powered by a 6 W PV-panel.

Fig. 22: PV-powered solar dryer (left) and a natural convection solar dryer (right), Honde Valley, Zimbabwe

4.2.2 Cabinet dryers with back-up heating

One significant disadvantage of solar dryers is that they are normally not used with any form of back-up heating. For commercial producers, this factor limits their ability to process a crop when the weather is poor. It also extends the drying time because drying can only occur during the daytime when there is adequate solar radiation. This not only limits production but can result in an inferior product. For commercial producers, the ability to process continuously with reliability is important to satisfy their markets [15].

Biomass, particularly fuel wood, is the most common source of energy in rural areas of developing countries, and provided unsustainable pressure is not placed on the local resource, fuel wood can be a greenhouse gas neutral source of energy, if usage is balanced by new plantings. It is currently often burned inefficiently and so there is need for simple, affordable combustion devices, which can be used to complement appropriate solar technologies such as the cabinet dryer.

4.2.2.1 Natural convection dryer with additional biomass back-up heater

A review of the literature indicates that there have been few attempts to overcome this limitation in simple natural convection solar dryers. One exception is the dryer reported by [16] which used a sawdust burner to provide heat during poor weather and at night. The burner was designed to provide 400 W/m^2 of energy to the drying cabinet, and used steam as the heat transfer medium. The sawdust burner was constructed as a separate component, rather than being integrated with the drying cabinet.

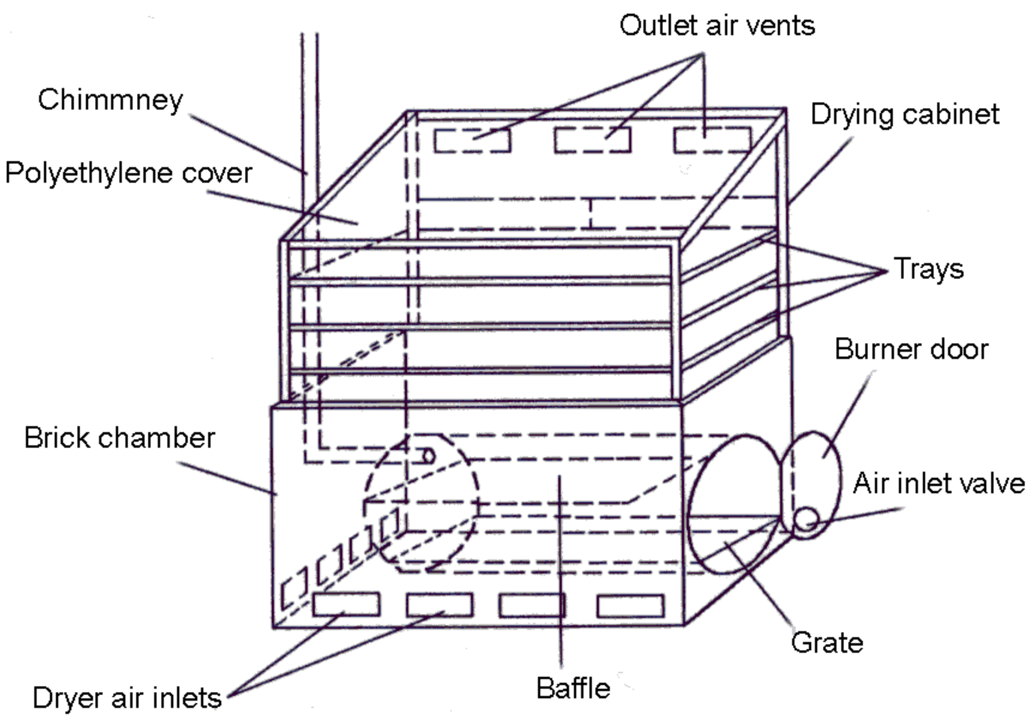


Fig. 23: Natural convection dryer with additional biomass back-up heater [15]

The dryer consists of a drying cabinet mounted on top of a brick chamber that encloses a simple biomass burner (Fig. 23 and Fig. 24). The outside base dimensions of this dryer are 1.2 m by 1.2 m. There are three drying trays, each with a wire mesh base, and in total these provide an effective drying area of ~ 3 m^2. The top surface is inclined to maximise the capture of solar radiation. The cabinet was constructed using pine wood and was covered with a single layer of 0.15 x 10^{-6} m thick UV stabilised polyethylene film. Access to the inside of the dryer is via two hinged doors at the rear of the cabinet. The drying trays slide on timber rails on the inside of the cabinet so that they can be removed from the dryer for loading, unloading and cleaning. Three adjustable vents, measuring 0.2 m by 0.05 m, are located at the top of the rear panel of the dryer above the doors. An aluminium mesh is fitted to the underside of the dryer to prevent insects reaching the crop through the brick chamber air inlets.

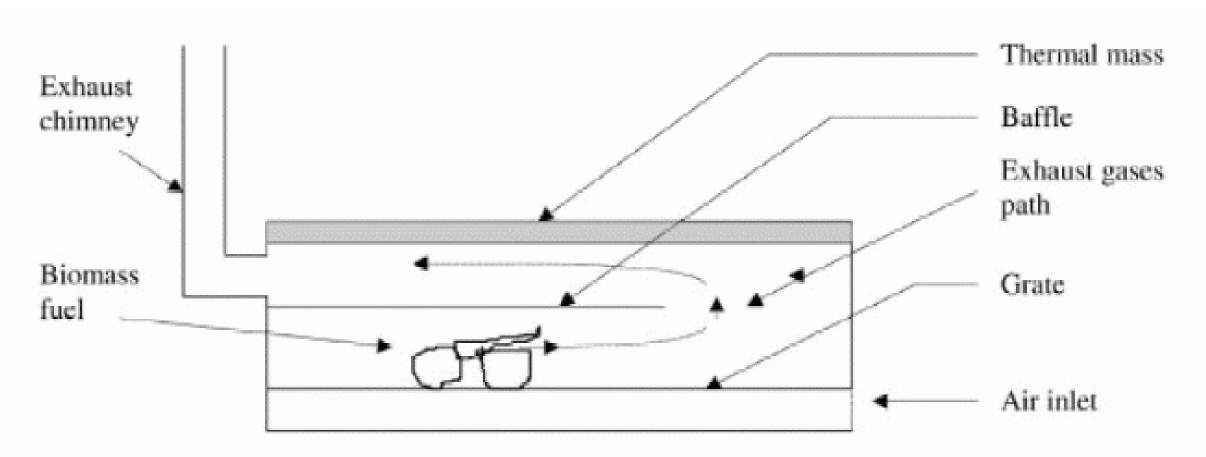


Fig. 24: Cross section through biomass burner. [15]

The biomass burner, designed primarily for fuel wood, was constructed from a 0.2-m drum laid on its side. The burner grate was constructed from a perforated tray, supported on rails riveted to the inside walls of the drum. The original lid was hinged to the drum as a door. A 0.2-m diameter hole was cut in the centre of the bottom of the door below the grate, and fitted with a simple 'spinning' valve to regulate the flow of air into the burner. The exhaust air exits via a 0.09-m diameter 1.8-m-long flue pipe located on the other end of the drum. In order to lengthen the flow path of the combustion gases and maximise the transfer of heat to the drum walls, a metal baffle was inserted above the grate and below the exhaust gas exit. Approximately 50 kg of concrete were added to the outside of the top surface of the drum to prevent excessively high air temperatures in the drying cabinet.

The brick chamber that supports the drying cabinet and encloses the burner was constructed such that there were 12 rectangular holes, each ~0.012 m^2 in area, around the perimeter at ground level. The gaps between the sides of the drum and the walls and between the top of the drum and the insect mesh on the drying cabinet are ~0.15 m and 0.2 m, respectively. The drying cabinet was fixed to the chamber with metal strapping mortared into the top layer of brick-work, and any gaps were sealed with mortar.

The dryer is designed to operate with solar radiation as the main source of energy. The back-up heater is used when radiation is inadequate and at night so that continuous drying is possible. When the dryer is operated using solar energy, radiation enters through the transparent cover, is absorbed by the interior surfaces of the cabinet and by the crop, and is converted into heat. The heated surfaces warm the surrounding air, which rises by natural convection, passing through the drying trays and picking up moisture. The moist air finally exits the dryer through the vents on the upper side of the cabinet. This action reduces the pressure inside the cabinet and ambient air is drawn into the dryer through the inlet holes in the brick chamber. A continuous flow of air is thus established. Varying the size of the opening of the air outlet vents can regulate the air flow rate.

During periods of low or zero solar radiation, the back-up heater located below the drying chamber is used to supply heat energy. The combustion gases heat up the drum surface, which in turn warms the air as it moves over the outer surface. The warm air rises up into the drying chamber and dries the crop as before. By regulating the amount of air entering the burner the heat delivery rate can be controlled. The type and location of fuel in the burner also influences the amount of heat generated and the period over which it is released.

When fully loaded with a single layer of 0.01 m thick slices of fresh pineapple, it was found that the capacity of the dryer was 20-22 kg. The pineapple slices took 3.5 days to dry from a moisture content of 59 %db to 11 %db during a trial. Approximately 47 % of the moisture in the slices was removed by solar energy, and the remainder by the biomass burner.

During biomass heater operation the maximum temperature of the air measured just above the bottom tray was 65.4 °C during night. The airflow through the dryer was estimated as 0.03 m^3/s. Approximately 9 kg of fuel wood (463 MJ) was burned on each night of a trial period. This, combined with 112 MJ from solar energy, was required to remove 18 kg of water to dry 21.6 kg of fresh pine apples slices to moisture content of 10 %db.

4.2.2.2 Hybrid IAE-type-solar-biomass dryer

The Institute of Agricultural Engineering (IAE) and the University of Philippines Los Banos (UPLB) [30] conducted a number of laboratory experiments under controlled conditions to determine the optimum drying parameters such as drying air temperature and the flow rate, thickness of fruit slices, etc., to achieve best quality products within a short period.

Analysis of the experimental results gave the following optimum drying conditions:

Fruits:	Temperature:	56 °C.
	Slice thickness:	3.5 mm.
	Air velocity:	0.31 m/s
Leaves:	Temperature:	68°C,
	Size of cut:	5.72 cm,
	Loading:	2.58 g/cm2

Based on these studies, IAE/UPLB decided to develop a cabinet type hybrid solar-biomass dryer suitable for small-scale drying applications with a capacity of about 50 kg/batch, referred to as Model FD-50.

The drying chamber has 30 aluminium wire screen trays to hold the products. The flat plate solar collector used has a single Plexiglas cover positioned about 5 cm above a matt black painted metal absorber sheet. All collector walls except for the transparent glass cover are insulated to 8 cm thickness to reduce heat losses. The solar collector is attached to the backside of the drying chamber at an angle of 15°. A 45 W exhaust fan fixed in the chimney of the drying chamber forces the ambient air to pass through the collector and rise up through the fruits being dried. The biomass gasifier stove assists drying whenever solar radiation is insufficient.

The design of the gasifier was adopted from the gasifiers developed at the Asian Institute Technology. It consumes about 2.0 kg of coconut shell or wood charcoal per hour and is capable of providing drying temperatures up to 60°C. The performance tests showed that a batch of 50 kg of sliced pineapple with an initial moisture content of 85% (wet basis) could be dried to a final moisture content of 20% in about 18 hours at a drying temperature of 60°C. A recovery rate of 10 kg of pineapple fruits was obtained. The total cost of the finished dryer was about P 56,000 (US$ 1,120 as of Feb 2002).

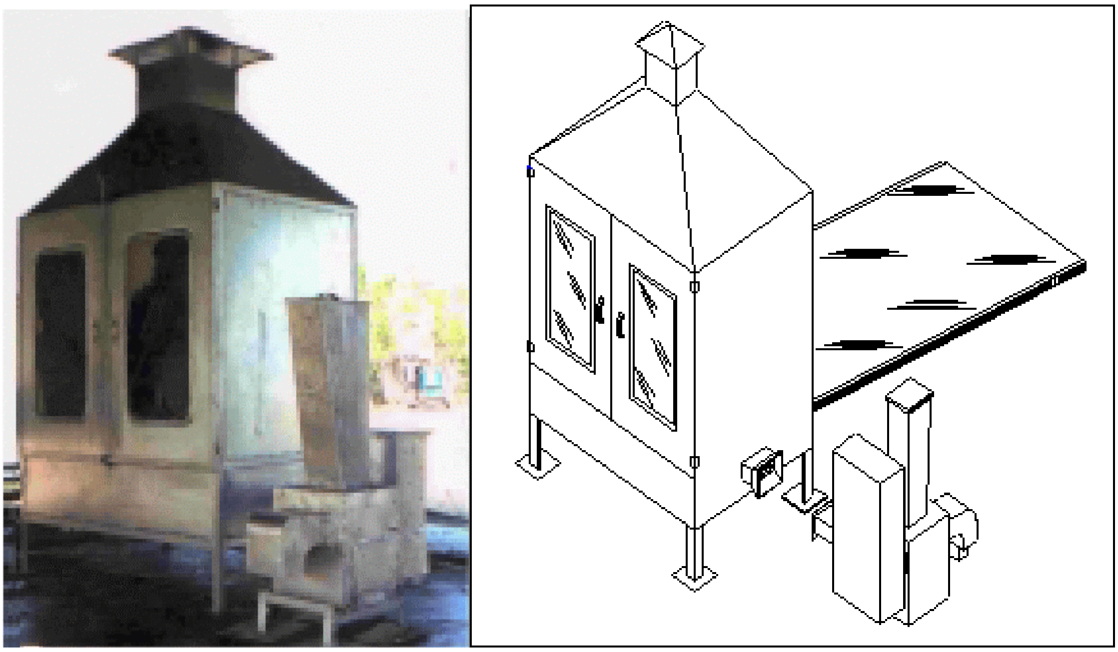


Fig. 25: Drying chamber and biomass stove of the FD-50 Dryer [30]

Table 5: Technical data of the FD-50 Hybrid Solar-Biomass Fruit Dryer

Capacity per batch	50 kg sliced fruit
Drying time	18 hrs
Drying air temperature	up to 60 °C
Air flow rate	0.05 m^3/hr
Dimensions	1.4 x 1.0 x 2.69 m
No. of trays	30 of 0.98 x 0.5 m
Solar collector area	2.12 x 0.9 m
Collector air gap	0.05 m
Fuel type	Coco shell/charcoal
Fuel consumption	2.0 kg/hr

A simple cost-benefit analysis was computed by [31] using the following assumptions: (1) 150 batches per year; (2) cost of pineapple fruit is Php 4 per piece; (3) cost of fuel is Php 50 per bag; (4) Dryer operator cost is Php 250 per batch; (5) cost of laborer is Php 60 per hour per person; (6) cost of dried pineapple is Php 19 per 100-gram; (7) Electricity cost is Php 5 per kWh; (8) Depreciation is straight-line method; (9) Repair and maintenance is 8 %; and (10) Interest rate is 18 %.
The summary of the computation is presented below. Note that the Philippine Peso is approximately equal to 50 US dollars. Cost of the solar-biomass drying system: Php 56,000.00 (US$ 1,120)
Yearly expenses: Total (including depreciation and interest): Php 256,771.00 (US$ 5,135.42)
Yearly income: Total sales of dried pineapple: Php 285,000.00 (US$ 5,700)
Net annual Income: Php 28,229.00 (US$ 564.58)
Pay-back Period: 56,000/28,229 = 1.98 ≅ 2 years

4.3 Greenhouse dryers

The idea of a greenhouse dryer is to replace the function of the solar collector by a green house system. The roof and wall of this solar dryer can be made of transparent materials such as glass, fibre glass, UV stabilized plastic or polycarbonate sheets. The transparent materials are fixed on a steel frame support or pillars with bolts and nuts and rubber packing to prevent humid air or rain water leaking into the chamber other than those introduced from the inlet opening. To enhance solar radiation absorption, black surfaces should be provided within the structure. Inlet and exhaust fans are placed at proper position within the structure to ensure even distribution of the drying air.

Designed properly, greenhouse dryers allow a greater degree of control over the drying process than the cabinet dryers [17] and they are more appropriate for large scale drying.

4.3.1 Natural convection greenhouse dryer

The earliest form of practically-realised natural-circulation solar greenhouse dryers reported was the Brace Research Institute glass-roof solar dryer in [6]. The dryer (see Fig. 26) consisted of two parallel rows of drying platforms (along the long side) of galvanised iron wire mesh surface laid over wooden beams. A fixed slanted glass roof over the platform allowed solar radiation over the product. The dryer, aligned lengthwise in the north-south axis, had black coated internal walls for improved absorption of solar radiation. A ridge cap made of folded zinc sheet over the roof provides an air exit vent. Shutters at the outer sides of the platforms regulated the air inlet.

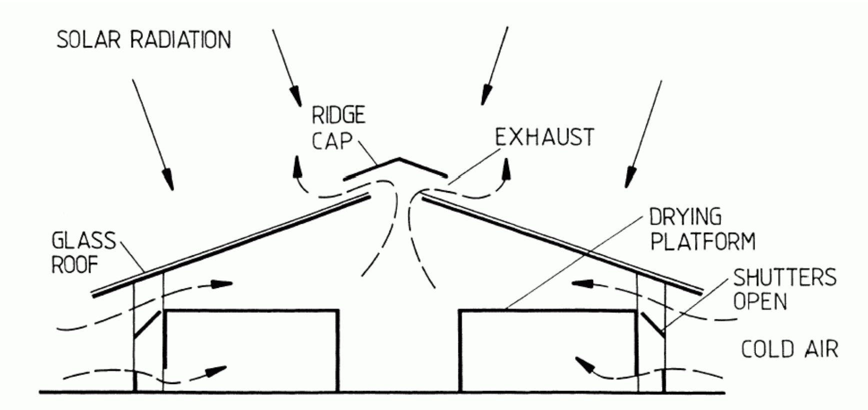


Fig. 26: Natural convection glass roof greenhouse dryer.[6]

A simplified design [6] of the typical greenhouse-type natural-circulation solar dryer consists of a transparent semi-cylindrical drying chamber with an attached cylindrical chimney, rising vertically out of one end, while the other end is equipped with a door for air inlet and access to the drying chamber (see Fig. 27). The chimney (designed to allow for a varying height) has a maximum possible height of 3.0 m above the chamber and a diameter of 1.64 m. The drying chamber was a modified and augmented version of a commercially-available poly-tunnel type greenhouse.
The dryer operates by the action of solar-energy impinging directly on the crop within the dryer. The crop and a vertically-hung, black absorbing curtain within the chimney absorb the solar radiation and are warmed. The surrounding air is, in turn, heated. As this heated air rises and flows up the chimney to the outside of the dryer, fresh replenishing air is drawn in from the other end of the dryer.

Apart from the obvious advantages of passive solar-energy dryers over the active types (for applications in rural farm locations in developing countries), the advantages of the natural-circulation solar-energy ventilated greenhouse dryer over other passive solar-energy dryer designs include its low cost and its simplicity in both on-the-site construction and operation. Its major drawback is its susceptibility to damage under high wind speeds.

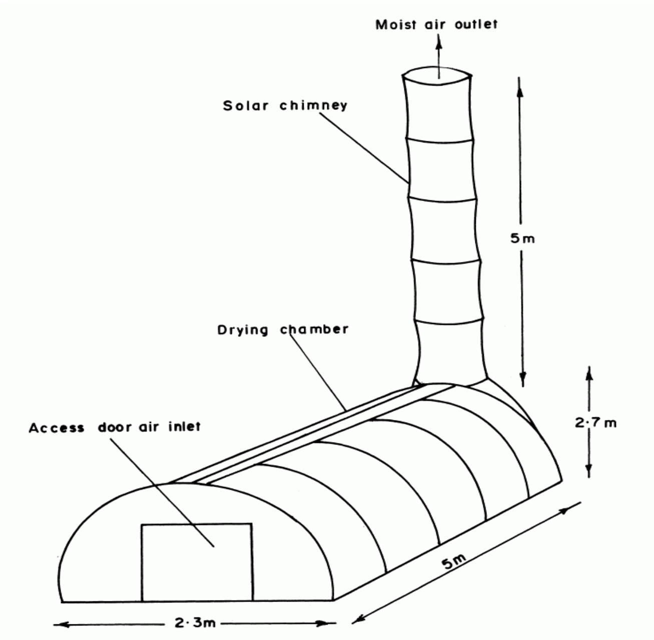


Fig. 27: Natural convection greenhouse dryer with chimney [6]

4.3.2 Greenhouse dryer with forced ventilation

Other designs of greenhouse solar dryers are shown in Fig. 28 and Fig. 29. In the case of Fig. 29 the whole structure stood on a 3.27 m side square blackened floor made of concrete. The height of the structure was 2 m on one side and 3 m on the other. In addition a blackened steel plate was installed at the upper position inside the structure leaving 0.5 m clearance for inlet air ducting to enhance the thermal performance.

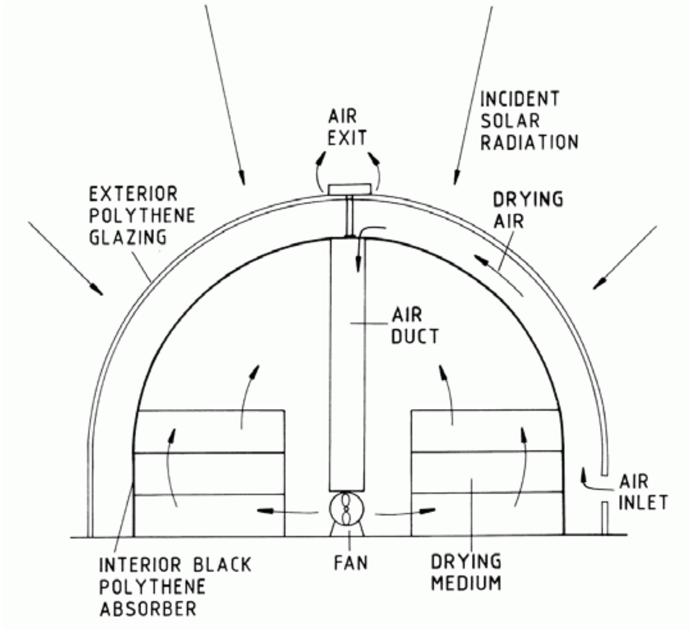


Fig. 28: Greenhouse dryer with forced ventilation.[6]

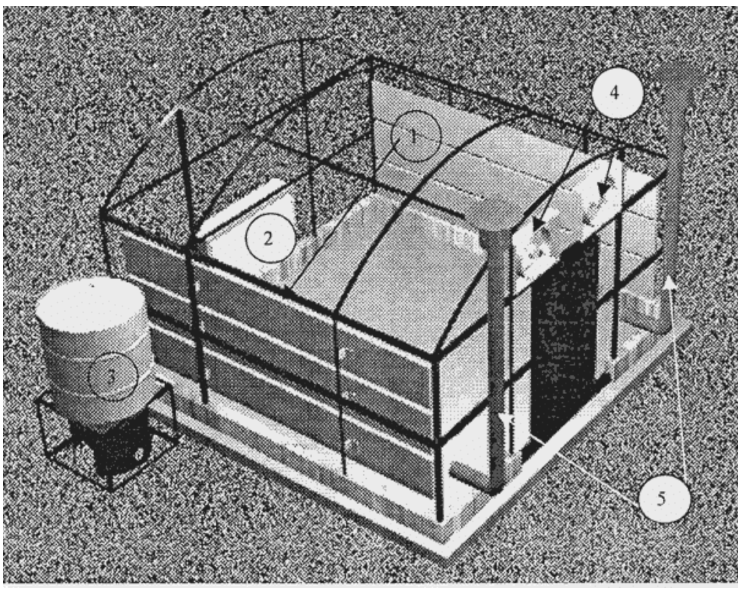


Fig. 29: Schematic diagram of a greenhouse solar dryer showing the radiation absorber (1), the heat exchanger (2) for auxiliary heating using hot water stored in a tank (3), the blowers (4) and PDIDs (5). At the centre, racks or drying bins can be placed. [24]

Two 80 W inlet fans were installed at the front wall above the door to deliver adequate primary air, which could create a drying temperature of around 50 °C. As shown in Fig. 29 to back up drying at night or during bad weather conditions, an auxiliary heating unit comprising of two heat exchangers, each provided with 100 Watt blowers were installed at the rear section within the transparent structure and were each connected with a biomass or kerosene fired hot water tank.

4.3.3 Continuous production greenhouse drying

An other design of a forced convection greenhouse dryer has been built and tested by Condorí et.al [32]. Its main parts are:

- a plastic greenhouse cover containing a drying tunnel made with transparent plastic walls;
- a line of carts with several stacked trays containing the product and moved manually inside the tunnel and an electrical fan that moves the hot air from the greenhouse into the tunnel.

This tunnel greenhouse dryer works continuously, obtaining a daily production. The maximum drying potential of the hot air coming from the collector area is mainly used in the first carts. Each day, dried product is removed from the tunnel, while an equal amount of new fresh product is loaded through its other end. As the air flows in a reverse sense — relative to the carts — the available energy is used efficiently. The trays receive solar radiation through the transparent walls, increasing the product temperature. Heat losses from the tunnel are low since greenhouse temperatures are higher than ambient temperature.

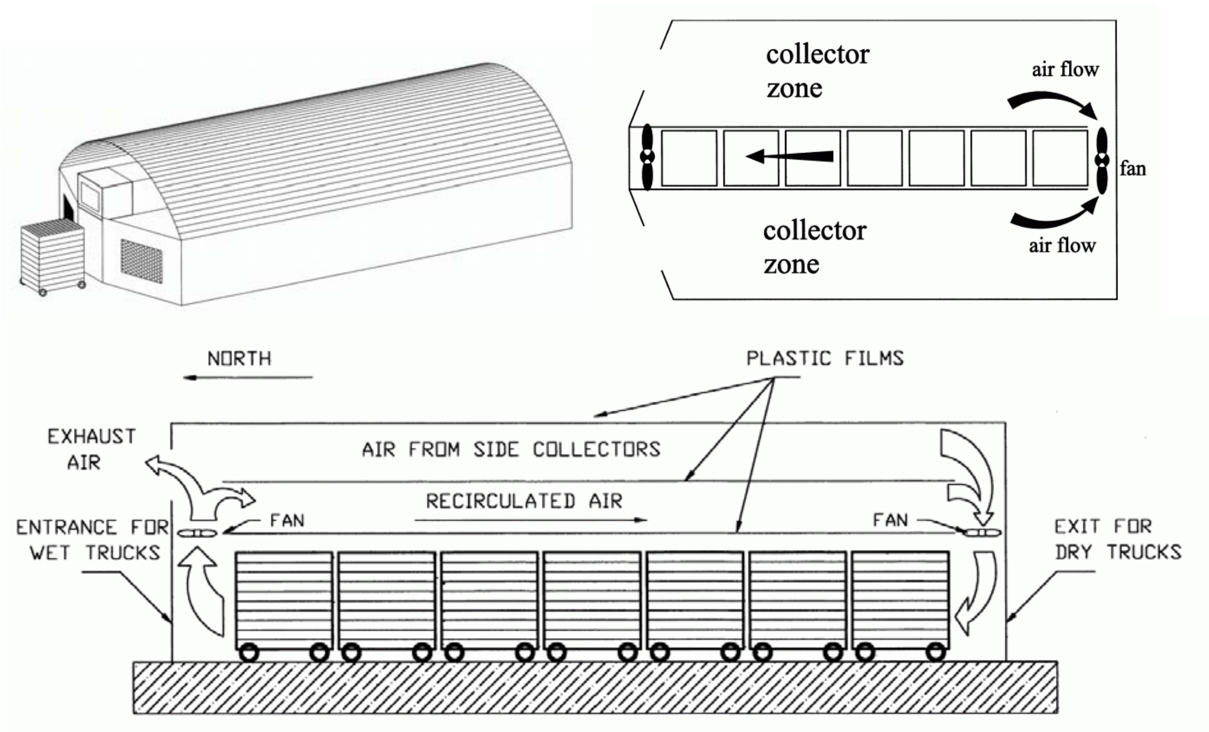


Fig. 30: Different views of the Tunnel Greenhouse Dryer. [32]

The main advantages of this dryer are:

+ an almost continuous production since some carts with dried product come out of the tunnel every day, while the same amount of fresh product is introduced by the other tunnel extreme;
+ lower labor cost since the product handling is partly mechanized;
+ a conventional heater can be easily installed to keep a constant production rate;

+ the energy consumption is lower than in other dryer types;
+ the installation can be used as a greenhouse for small production when it is not used as a dryer.

The prototype was built in the North of Argentina, and red sweet pepper and garlic were used as load. Sweet pepper halved is used as fresh product; it is distributed on the cart trays using a load density of 5 kg by m² of tray surface. The pepper is harvested according to its maturation in the plant, one or two times a week, and it is immediately washed and put on the trays in the dryer.

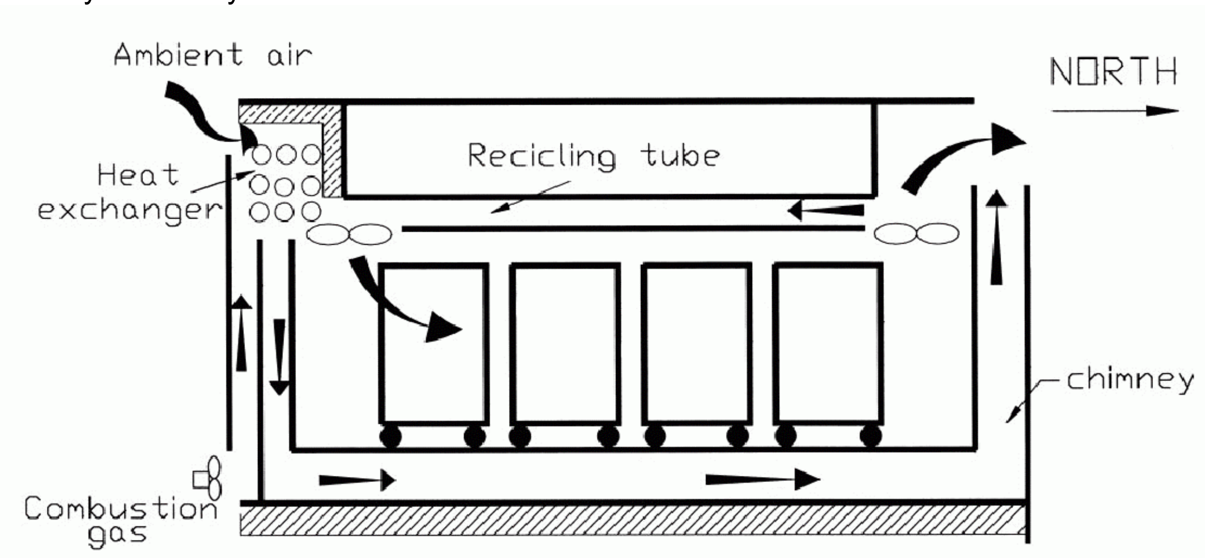


Fig. 31: Operation scheme of the tunnel greenhouse dryer with auxiliary heating. [32]

As it is usual in solar applications, the low radiation density and the variability of the energy source are the main problems to solve. It is quite simple to add an auxiliary heater to this dryer. Fig. 31 shows the operation of this system either in cloudy days or at night. The collector ambient air input is closed improving the thermal insulation, since it produces an air chamber with low natural convection surrounding the drying tunnel. The ambient air is taken directly from the outside South side, and it is pushed by the fans through an unfinned tubular heat exchanger, where it is indirectly heated by the combustion gas flowing inside the tubes. Then, the heated air moves through the file carts as before. The hot gas is produced by a forced flow stove, fed with firewood or agricola surplus. The remaining cooler combustion gas is expelled to the environment by a chimney. Both the heat exchanger and the stove are insulated to avoid heat losses and to protect the plastic cover.

4.4 Tunnel dryers

More than ten years of research and field testing has resulted in the development of a solar tunnel dryer well suited to medium sized farms or small cooperatives. The non-patented design was developed at the University of Hohenheim, Germany [21], and has been duplicated successfully throughout the world. A key to this success has been the adaptation of the dryer design to the local climate and manufacturing possibilities in multiple countries. By 2003 over 1,000 Hohenheim type solar dryers were in use in 60 countries [22]. Over half of these dryers were manufactured in the country of use; the rest were supplied by Innotech, a German corporation manufacturing prototypes of the dryers. Innotech supplies the dryers in kit form for roughly 5,500 US$ (2000), for use in locations where manufacturing has not yet been established. Innotech also offers a consultancy for quality assurance and marketing of dried products for export to industrial countries.[23]

The Hohenheim-type dryer results in faster drying and higher quality than traditional open-air methods. In Turkey, for example, apricots can be dried in 2 days – half the time required by traditional methods. An important feature contributing to consistent quality is the use of photovoltaic powered fans for forced convection. The controlled drying process results in high-quality. The acceptable load for the dryer ranges from 1.5 kg/m² for medicinal herbs to 25 kg/m² for rice or coffee. For a standard dryer with a 20 m² drying area, this corresponds to 30 to 500 kg per batch.

Some dryers made in Thailand are equipped with a gas powered air-heating unit to allow drying during the six-month rainy season. In contrast, Turkish weather is dry enough to allow the all-solar dryers to operate well with twice the standard drying area. Local manufacture of the Turkish models allowed a total installation cost of less than 1000 US$ in 1997, resulting in a payback period of only one year. The models used in Thailand were more expensive due to the gas-powered back-up heating unit.

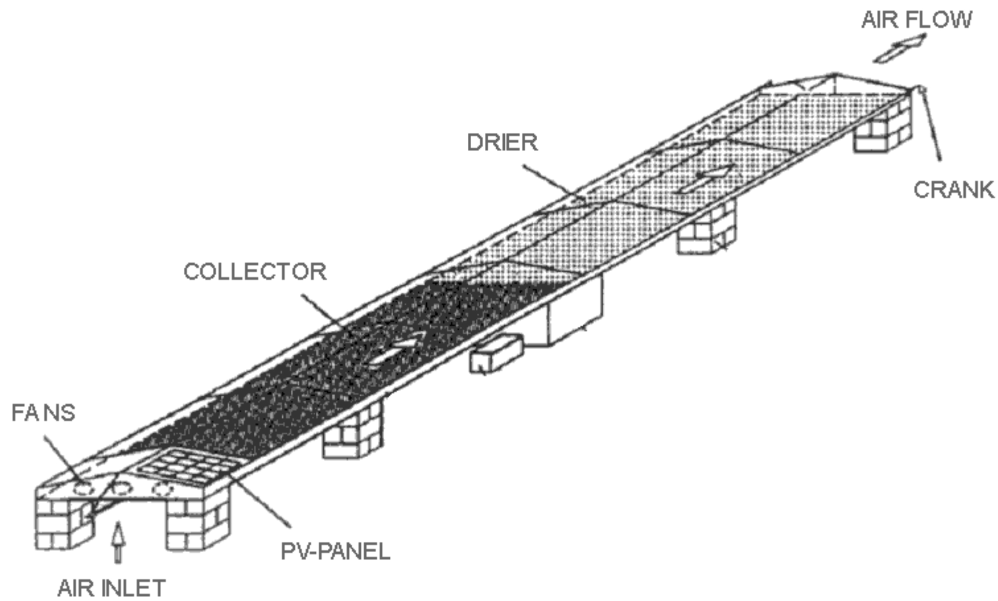


Fig. 32: Solar Tunnel Dryer

The three major dryer components, as shown in Fig. 32, are the solar collector, food dryer compartment, and the airflow system. Air is circulated by fans, which use from 20-40 W of power from a photovoltaic panel, a generator, or a central utility. Air is forced into the solar collector by the fans where it is heated by the sun, and then flows on to the food dryer section. An advantage of the PV powered system is that, depending on the solar radiation, the air throughput is automatically adjusted by the speed of the fans. The plastic cover may be constructed from a sheet of greenhouse type UV-stabilized polyethylene (PE).

Access to the drying chamber is gained by removing the plastic covering using the hand crank. The crop is placed on a polyester mesh suspended by a grid of galvanized wire. This arrangement allows air to flow on all sides of the food, preventing the need to turn it during the drying process. Depending on local circumstances a dryer may be built in a permanent installation (with concrete, for example), or in a portable construction. When introduced in a new region, the tunnel dryer often requires customization to suit the local climate and manufacturing possibilities. Often a prototype is adapted and tested before proceeding with local manufacture.

Hohenheim engineers have produced a set of design specifications to help insure quality performance. As long as these design specifications are followed, considerable opportunities exist for successful variation of the dryer. Table 6 shows some of the options viable for making each part of the dryer.

Table 6: Options for adapting a solar tunnel dryer [23]

PART	OPTIONS
Support	Stone, slate, wood, metal, loam, barrels
Frame	Steel sheeting, wood, plywood, slate, concrete, stone, loam
Heat insulation	Polyurethane, Styrofoam, building insulation, cork, flax, straw, coconut fibers, wood shavings, leaves
Sheeting (cover)	LD-PE, LLD-PE, PTFE, PVC, PE-EVA
Winding shaft	Steel pipe, plastic, wood, bamboo, wicker
Power source	Photovoltaic cells, utility power, diesel or petrol generator

Fig. 33: Pictures of the solar tunnel dryer

Table 7: Technical data of the tunnel dryer

Length	18 m
Width	2 m
Collector area	16 m²
Drying area	20 m²
Air flow rate	400-1200 m³/h
Air temperature	30-80°C
Power requirement	20 - 40 W
Thermal energy gain from solar radiation	up to 60 kWh/d (≅15 kg firewood)
drive of fans	solar panel
Number of fans	3
Price	US$ 5,250 (+US$ 250 for PV)
Products	Indirect operation ideal for sensitive products
Climate	Operation in arid and humid regions; adaptable to local climate
Control	Self regulated airflow and temperature (solar panel type)

4.5 In-House Dryer

In-house dryers work with the same principles as active indirect solar cabinet dryers. They consist of solar air collectors, one or more fans and drying trays. Due to its size and other convenience and hygiene factors, the construction to carry these elements is a house where the roof is build by the solar air collectors. Additional heating can be provided.

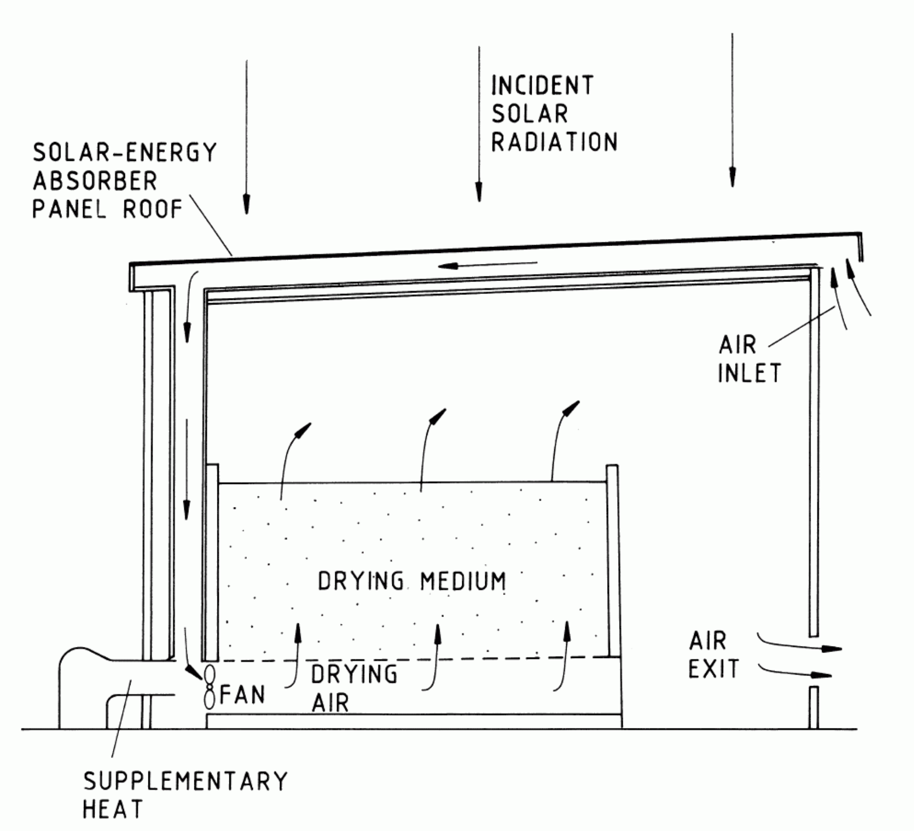


Fig. 34: A collector roof active storage dryer. [6]

The in-house solar dryer shown in the following pictures (Fig. 35 and Fig. 36) was erected near Accra in Ghana [25] and used for maize for seed and pineapples.

The dryer consists of 5 identical drying units with a total solar air collector array of approx. 25m², a PV-area of 3.2 m² and a drying bed with a capacity of approx. 500 kg maize. The 5 drying units are located in a building erected for that purpose and with the solar air collectors being the roof of the building. The five drying units were manufactured in Denmark and shipped to Ghana.

The decision to build 5 equal units based on the following considerations:

- ✓ If one drying bed is operated improperly this will not affect the total quantity of crops being dried at that time.
- ✓ It is possible to dry different crops (creating different pressure drop) side by side without risking that the crop with the highest pressure drop will be dried improperly.
- ✓ Small DC-fans are often cheaper than larger DC-fans.
- ✓ The system is less complex, and an even air distribution over the drying bed is easier obtainable.
- ✓ It is possible to start with only one unit and then gradually increase the capacity of the solar dryer.

Fig. 35: In-house type solar crop dryer in Ghana [25]

Table 8: Technical Data of one unit

Collector		
	Outer dimensions	4.9 x 1.07 m
	Transparent area	4.77 m²
	Cover	10 mm double walled ribbed UV-stabilized polycarbonate
	Absorber	black felt mat. Air intake at the back of the PV-panels at both ends and air outlet in the middle at the back.
Fan		
	Flow rate	300 m³/h at 40 Pa
	Voltage	12 V DC
	Power	12 W
PV		
	Number	2
	Voltage	12 V
	Power	14 W_P
Duct		
	metal ducting with the smallest cross section of 0.031m²	
Drying bed		
	Number	6 trays made of plastic
	outer dimensions:	600 x 400 x 278 mm

It should be noted, that with an air flow rate of 300 m³/h per unit the air speed through the drying bed was 0.06 m/s. This is very low compared to the 0.3 -0.7 m/s in conventional cross flow dryers and also low compared to the 0.1 m/s in conventional platform dryers. The low air speed, however, results in a longer drying time. With the chosen concept it is not possible to dry maize in one day – two-three days are needed.

Fig. 36: Inside the in-house type solar crop dryer in Ghana [25]

5 Non-technical aspects

A huge advantage of solar dryers is the fact that different types of fruits and vegetables can be dried. The quality of products dried in this way is excellent, due to the fact that the food is not in direct sunlight (cabinet or in-house dryer), and due to a shorter drying process – up to a 1/3 of the time in comparison to traditional sun drying.

The drying operation must not be considered as merely the removal of moisture since there are many quality factors that can be adversely affected by incorrect selection of drying conditions and equipment. The desirable properties of high-quality, e.g. for grains, include:

- low and uniform moisture content
- minimal proportion of broken and damaged grains
- low susceptibility to subsequent breakage
- high viability
- low mould counts
- high nutritive value
- consumer acceptability of appearance and organoleptic properties.

Even where there is a demand for loss reducing technical changes, farmers may find it difficult to adopt recommended technologies, because of cash flow problems, labour constraints, or lack of materials. Small farmers and traders often find it difficult to obtain credit at reasonable interest rates, since formal financial institutions consider loans to them be too risky.

A very important prerequisite for the successful utilisation of the solar dryer is the access of the producer to the market and the knowledge of the specification of the customers. It is of great importance that there is a price differentiation according to the product quality and that people are requesting and willing to pay for the more hygienic product.

Fig. 37: Hygienic packing is necessary if the drying goods shall be sold on commercial basis.

5.1 Drying behaviour

Apart from weather conditions the drying behaviour of agricultural crops during drying depends on the [1]:

- Product
- Size and shape
- Initial moisture content
- Final moisture content
- Bulk density
- Thickness of the layer
- Mechanical or chemical pre-treatment
- Turning intervals
- Temperature of grain
- Temperature, humidity of air in contact with the grain
- Velocity of air in contact with the grain

Look for details about the physics of drying in the appendix.

5.2 Weather conditions

The performance of solar dryers is significantly dependent on the weather conditions. Both the heat required for removing the moisture as well as the electricity necessary for driving the fans are generated in the most cases by solar energy only. In addition to the pre-treatment of the product, the weather conditions have the biggest influence on the capacity of product that can be dried within a certain time period.

The drying time is short under sunny conditions and accordingly extended during adverse weather conditions. The difference in drying capacity between dry and rainy season has to be taken into consideration for the calculation of the yearly capacity of the dryer.

The utilisation of solar energy as the only energy source is recommended for small-scale dryers where the risk of spoilage of big quantities of crops due to bad weather is low.
If large-scale solar dryers are used for commercial purposes it is strongly recommended to equip the dryer with a back-up heater to bridge periods with bad weather (see also chapters 4.1.5 and 4.2.2).

5.3 Storage

For small farmers the main purpose in storing grains is to ensure household food supplies. Farm storage also provides a form of saving, to cover future cash need through sale, or for barter exchange or gift-giving. Grain is also stored for seed and as inputs into household enterprises such as beer brewing, or the preparation of cooked food.

There is an ongoing debate about whether farmers are forced to sell because of debt and economic dependence on others, or whether they sell because they regard storage as

- too costly (in terms of time), or
- too risky (given the risk of losses and unpredictability of future prices), or
- unprofitable in relation to other investments such as cattle.

There is no single answer to the debate, since there is much variation in the circumstances under which individual farmers operate, both within and between nations [26].

5.4 Capacity

The capacity of a solar dryer mainly depends on the crop itself and the shape. On the one hand, it should not be too big to ensure that the preparation (washing, slicing and pre-drying processing) of the product to be dried can be completed within a certain time period. On the other hand it should be big enough to enable the user to generate income and thus to create new jobs.

5.5 Selection, cleaning and pre-treatment

A process similar to the following seven steps is usually used when drying fruits and vegetables (and fish, with some modifications) [27]:

1. Selection (fresh, undamaged produce)
2. Cleaning (washing & disinfection)
3. Preparation (peeling, slicing, etc.)
4. Pre-treatment (e.g. sulfurizing, blanching, salting)
5. Drying
6. Packaging
7. Storage or sale

Only fresh, undamaged food should be selected for drying to reduce the chances of spoilage and to help to ensure a quality product. After selection, it is important to clean the produce. This is because drying does not always destroy micro organisms, but only inhibits their growth. Fruits, vegetables, and meats generally require a pre-treatment before drying. The quality of dried fruits and vegetables is generally improved with one or more of the following pre-treatments: anti-discoloration by coating with vitamin C, de-waxing by briefly boiling and quenching, and sulfurization by soaking or fumigating. Fish is often salted. A small amount of chemical will treat a large amount of produce, and thus the cost for these supplies is usually small. However, potential problems with availability and the complexity of the process should be considered.

Fig. 38: Slicing of sweet potatoes (left) and bananas (right) before drying

After selection, cleaning, and pre-treatment, produce is ready to place in the dryer trays. Solar dryers are usually designed to dry a batch every three to five days. Fast drying minimizes the chances of food spoilage. However, excessively fast drying can result in the formation of a hard, dry skin - a problem known as case hardening. Case hardened foods appear dry outside, but inside remain moist and susceptible to spoiling. It is also important not to exceed the maximum temperature recommended, which ranges from 35 to 45°C depending upon the produce. Learning to properly solar dry foods in a specific location usually requires experimentation. For strict quality control, the drying rate may be monitored and correlated to the food moisture content to help determine the proper drying parameters (see the Appendix A for more information).

After drying is complete, the dried produce often requires packaging to prevent insect losses and to avoid re-gaining moisture. It should cool first, and then be packaged in sanitary conditions. Sufficient drying and airtight storage will keep produce fresh for six to twelve months. If possible, the packaged product should be stored in a dry, dark location until use or sale. If produce is to be exported, it must meet the quality standards of the target country. In some cases this will require a chemical and microbiological analysis of dried samples in a laboratory [27].

Food drying requires significant labour for pre-treatment (except for grains), and minimal involvement during the drying process such as shifting food to insure even drying. Solar drying equipment generally requires some maintenance.

6 Applications and experiences

The following chapters show examples of applied drying systems and different experiences from all over the world.

6.1 Fruit and vegetable drying

6.1.1 Table-like solar dryer, Tanzania

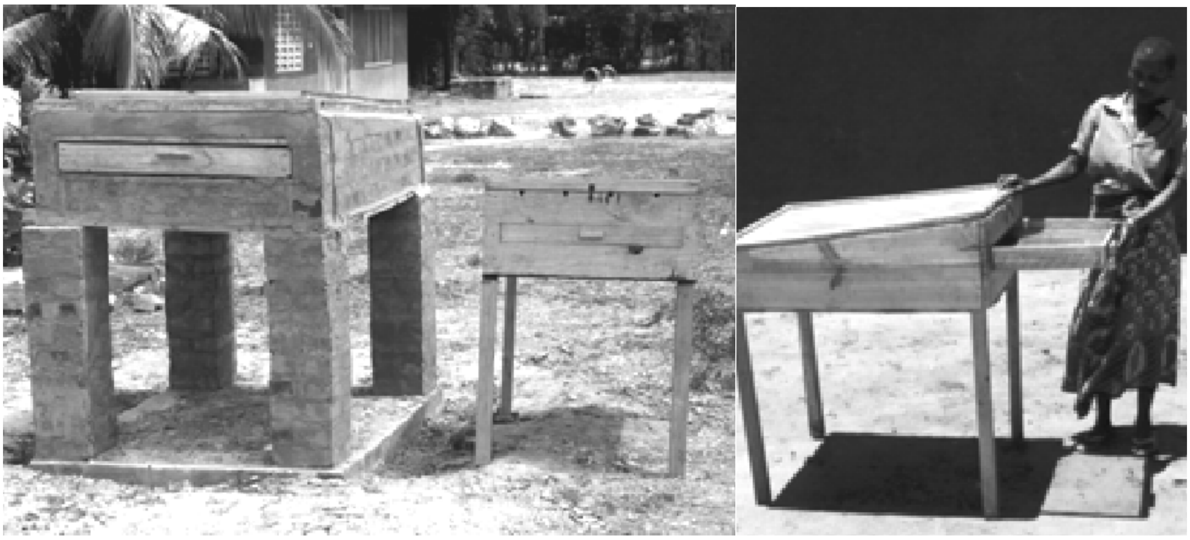


Fig. 39: Small solar dryers for families in Tanzania [28]

Fig. 39 shows two designs proposed to women by the *International Center for Research on Women (ICRW)* and the *Tanzania Food and Nutrition Centre (TFNC)* [28]. The main idea of the project was to strengthen women's contributions to reducing iron and vitamin A deficiencies by combining women's productive and reproductive activities. Those two solar dryer designs were developed based on lessons learned by TFNC from earlier solar dryer promotion and on input from community women.

One dryer was principally made from wood, which is lightweight and, therefore, portable, enabling women to position the dryer to maximize trapping solar energy at different times in the day (enhancing its effectiveness). It was, however, somewhat expensive. The other dryer was mud brick and less expensive than the wooden dryer. The heat retention of this dryer was enhanced by the thickness and poor heat conduction of the brick walls, thereby contributing to its drying effectiveness. However, this dryer was prone to deterioration over time even though the outer walls were coated with used motor oil to reduce rain damage.

Women chose the dryer they wanted to construct and provided all materials needed for the construction. Bulk purchasing of black cloth or plastic sheeting for the dryers was facilitated by TFNC to reduce the unit cost. The cost of materials and labor of the artisan or carpenter for a wooden dryer was approximately 8000 Tanzanian shillings (US$12). Mud-brick dryers cost less than half this amount (3500 Tanzanian shillings or US$5). Annual maintenance costs would be approximately US$2 for plastic sheets (black or transparent) and wire mesh for the drying tray.

Once the materials were procured, a dryer could be constructed in one day**.** While the women or other household members did not construct the dryers themselves (actual construction was done by the carpenters or artisans), they worked alongside those technicians to learn the process and techniques of dryer construction. However, because the dryers' design and construction is relatively simple, artisans and carpenters are not required to build the dryers. The involvement of these technicians in this study was to enhance the diffusion of the dryers and to provide technical support for the adopter households.

Both types performed equally well for drying vegetables. Each dryer could produce approximately 1.5 kg of dried vegetables, if the vegetables were thinly spread to facilitate faster drying. On average, the dryers were used three times a week, with drying times ranging from four to six hours per use, depending on the type of vegetable and intensity of the sun. For example, it would take about four hours to dry amaranth (*mchicha*) leaves on a sunny day, but six hours for sweet potato leaves. Drying one kilogram of fresh vegetables would yield approximately 250 grams of the dried food product.

6.1.2 Banana dryer, Brazil

The solar dryer system introduced by Costa [29] is operating in a mixed mode, which uses indirect heating through forced convection, which gives high yield and good quality for the dried product.
The system is composed of:

- An electrical ventilator allowing an independent air flow rate;
- A solar collector in which its characteristics and dimensions were determined according to hot air flow rate and operating temperature;
- A special designed dryer for tropical fruits;

A scheme of the solar dryer is shown in Fig. 40. The innovation of this work is not only in the dryer design and dimension, but also in its configuration, material and in the solar collector dimension. The collector was constructed in such a way that its use can be versatile. It is made of flexible PVC, in a cylinder shape with two cones at the both ends. At the bottom, 50% of the collector is made of dark plastic in order to absorb heat and at the top with transparent plastic, in which the solar rays penetrate.

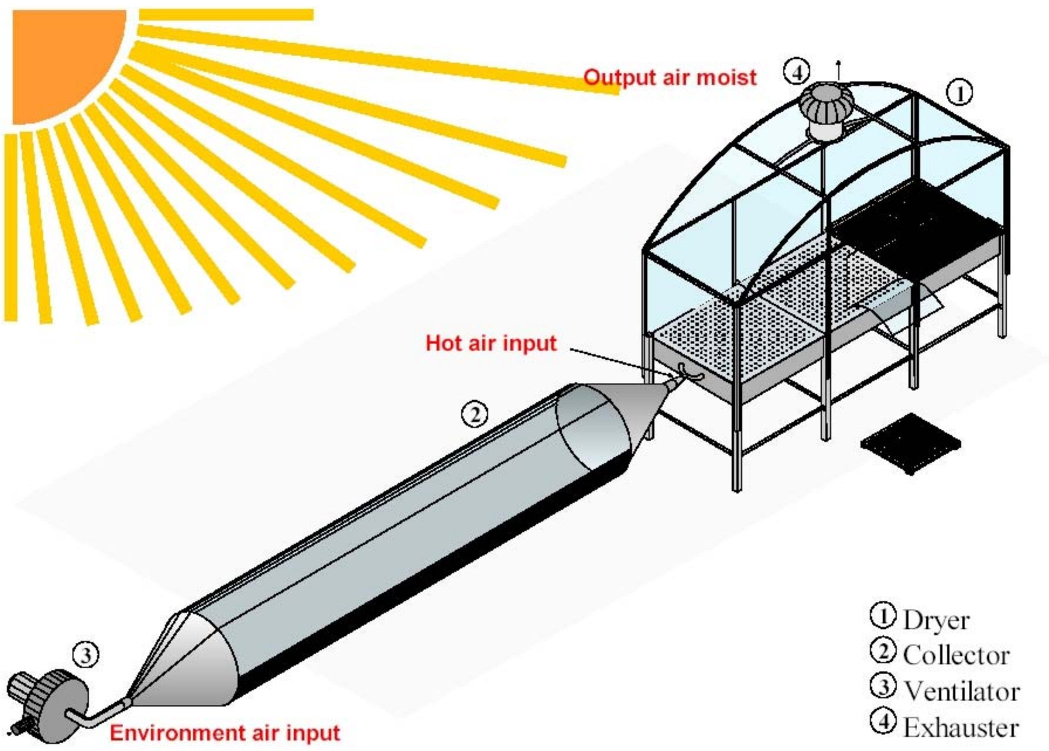


Fig. 40: Scheme of the solar dryer for bananas

Fig. 41: Pictures of the solar banana dryer

The dryer also works as a solar collector, because it was constructed of transparent PVC and the aluminium support offers good heating and transport conditions. The trays, which contain the fruits to be dried, can be arranged one on top of the other. An exhauster provides air circulation, through an exit in the superior part.

6.1.3 Mango dryer, Uganda

MS-Uganda (Danish Association for International Cooperation) [5], together with Hoima Nursery Schools Development Association, Gukvatamanzi Farmers´ Association and its other partners in Uganda, had introduced locally made solar dryers to small-scale and community-based farmers to help them to create income.

The fruit dryer is designed from basic materials locally available and constructed by local crafts-men. The solar dryer consist of:

1. A wooden frame, constructed as box with shelf for the fruit trays
2. A number of trays made of wooden frame with nylon chicken nets, which allow the air circulation
3. A transparent plastic (acrylic glazing), used as glazing keeping and increasing the heat capacity
4. Used oil around the dryer’s legs to protect the wood from being eaten by termites and prevent access of ants and termites to the fruits.

Fig. 42: Pictures of the Mango solar dryers in Uganda (passive direct solar cabinet dryer) [5]

The affordable price of the solar dryer, made it possible for the above mentioned organisations to invest in the development and testing of the solar dryer. The cost of the dryer shown in the picture above is about 90.000 Ush – equivalent to 70 US$. This price is still a high price compared to the ability of the end-users, who in general are small-scale farmers or women groups. They are not able to pay for the dryers in cash. Therefore small soft loans were established by the CRS for first time investments.

6.1.4 Fruit and vegetable drying in Senegal and Burkina Faso

OSAKWE and WEINGARTMANN [33, 34] developed an in-house type solar dryer for fruits and vegetables. In many projects these systems had been erected in Burkina Faso and Senegal. A huge advantage of these systems, which are increasingly approved by users, is the fact that different types of fruit and vegetables can be dried, e.g. tomatoes, onions, cabbage, okra, carrots, hibiscus blossoms, mangoes, bananas and pineapples.
The quality of products dried in this way is excellent, due to the fact that the food is not in direct sunlight, and due to a shorter drying process – 1.5 days in comparison to 4 – 5 days for traditional drying.

In Burkina Faso the dryer where build inside a 6 x 4.5 m² house with a 15° inclined roof. The house consists of three rooms, one for preparing, one for storage and the drying room. The house has the advantage of being more hygienic and resistant to rainfall and wind. Erecting the house was supported through local craftsman. Two locals have been instructed in maintenance of the drying system. The local organisation of woman were trained in food processing, hygiene and marketing.

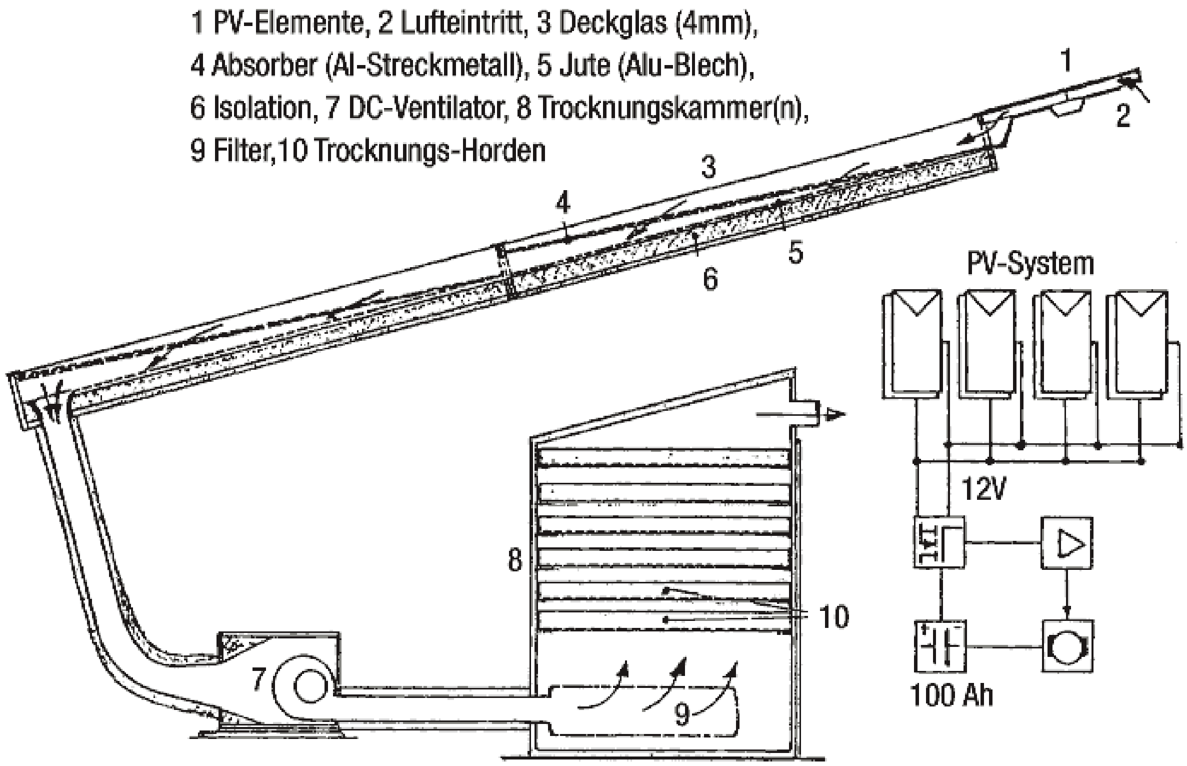


Fig. 43: Features of the active solar dryer in Burkina Faso

The production rate was about 12-14 kg of dry Mango in 2 days (12 % d.b.) which means that within 3 months 500 – 600 kg dry Mangos can be produced. The drying time could be reduced from 4-5 days down to 1.5-2 days.

Table 9: Technical data

Collector		
	Total area:	9 m²
	Outer dimensions:	2,02 m x 0,79 m x 0,23 m
	Material	Wood, aluminium, glass
	Number of collectors:	6
	Insulation:	8 cm
PV		
	Numbers:	2 parallel
	Voltage:	24 V
	Power:	each 110 W_P
	Accumulator:	2 x 60 Ah, 12 V, serial
Dryer		
	Total drying area:	12 m²
	Frame:	wood
	Trays:	aluminium
	Max. temperature:	65 °C (80 °C @ 176 kg/h air flow rate)
Fan		
	Air flow rate	445 / 750 m³/h
	Power	65 / 145 W


Fig. 44: Mango slices being placed on a drying tray (left); Assembling the collector on the roof (right), Burkina Faso. [34]

6.2 Coffee Drying

After oil, coffee is the largest volume commodity sold in the world. Much of the world's coffee has been dried using wood but increasingly processors are turning to fossil fuels.

A coffee cherry has a relatively thick skin, which encloses the parchment. The green coffee at 10 % moisture contains starch (10 %) protein (13 %) and caffeine (1,2 %). The coffee cherry can be considered to consist of two distinct layers; namely, the outer skin and the parchment separated by an air space. [35]

During drying moisture from the centre of the cherry has to move through the parchment, the intervening air space and the outer skin before it leaves the cherry. Diffusion coefficient, drying characteristics and rates were determined by [35]. A further test showed that the quality of the coffee (cup) did not change over the range of drying temperature (40-60 °C).

The drying season in Zimbabwe for instance, runs from approximately June through September providing a long operating time for drying equipment. Drying takes place at relatively low temperatures (40^o to 75^oC) and with relatively high air flows making it an ideal application for solar energy. Wet processed beans require to be dried from a humidity of 50-55% to about 11%. This is typically accomplished in large commercial drying applications in about 19 hours usually using a combination of pre-drying to remove surface water, vertical dryers and drum dryers. [36]

Fig. 45 is a schematic of the three processes. The green broken line shows the coffee beans flowing through the pre-dryer first then to the vertical dryer and finally to the drum dryer. In this case a single furnace maintains drying air at 60°C and tempering is used to maintain the delivered air temperature at the appropriate level.

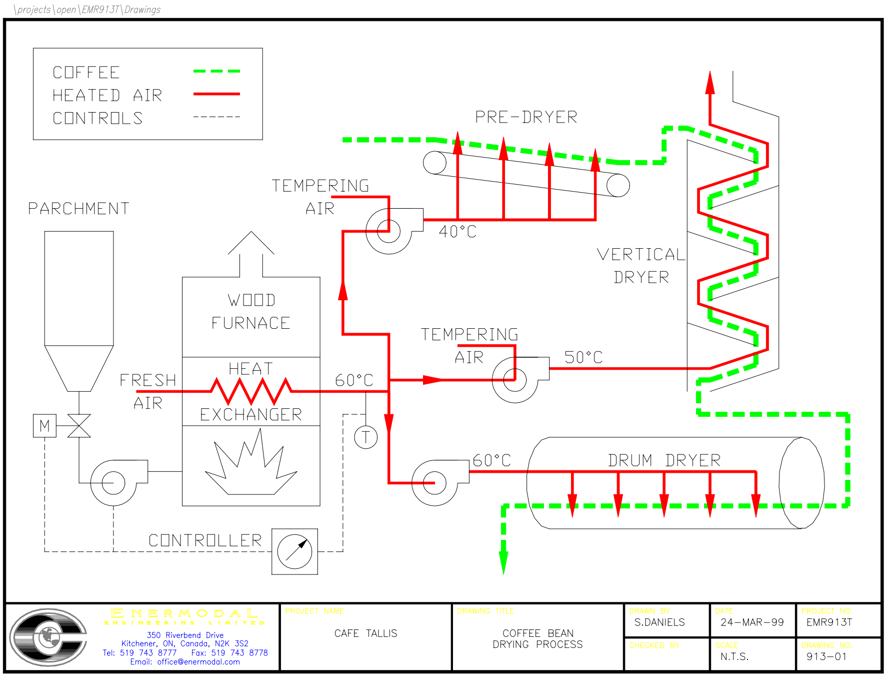


Fig. 45: Typical coffee bean drying process [36]

6.2.1 *Large scale combined biomass and solar coffee drying*

One opportunity for large scale coffee drying is a hybrid system, containing two independent sources of thermal energy –solar and biomass.

Under normal conditions (day and sunshine) solar air collectors are used to heat up the air for coffee drying. To enable a continuous drying, during night time the hot air for the drying process is provided by a wood furnace.

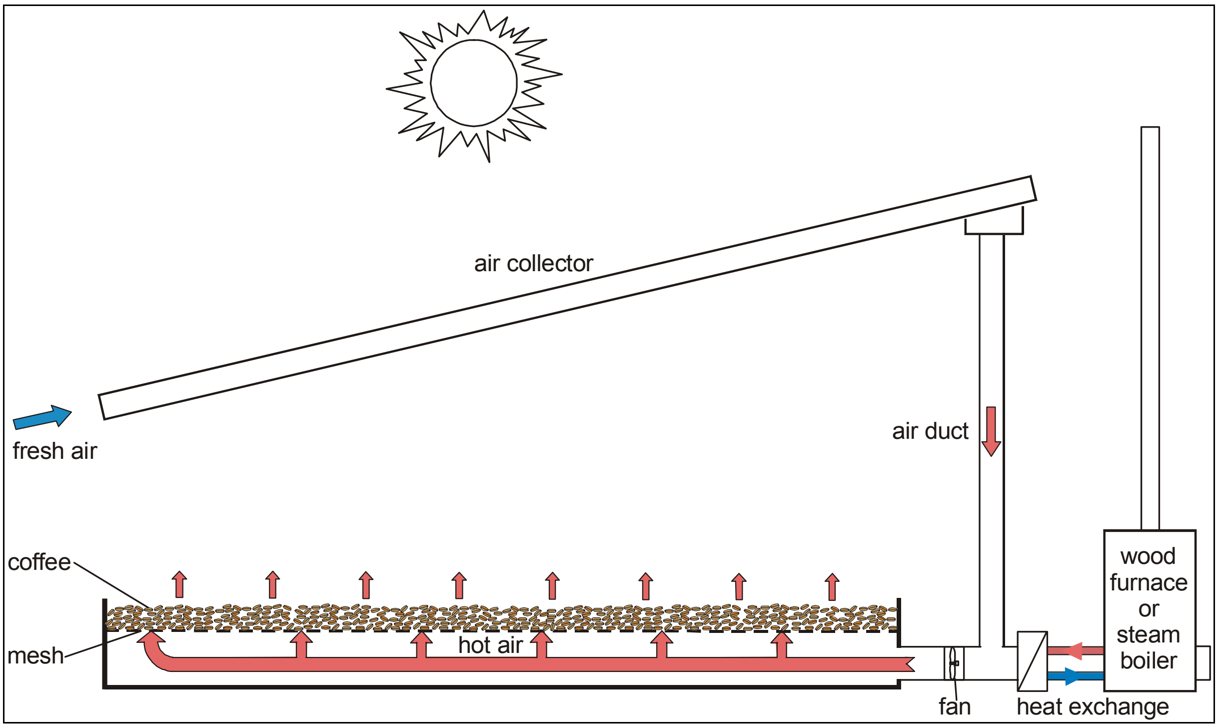


Fig. 46: Solar coffee drying system using a wood furnace as back-up system

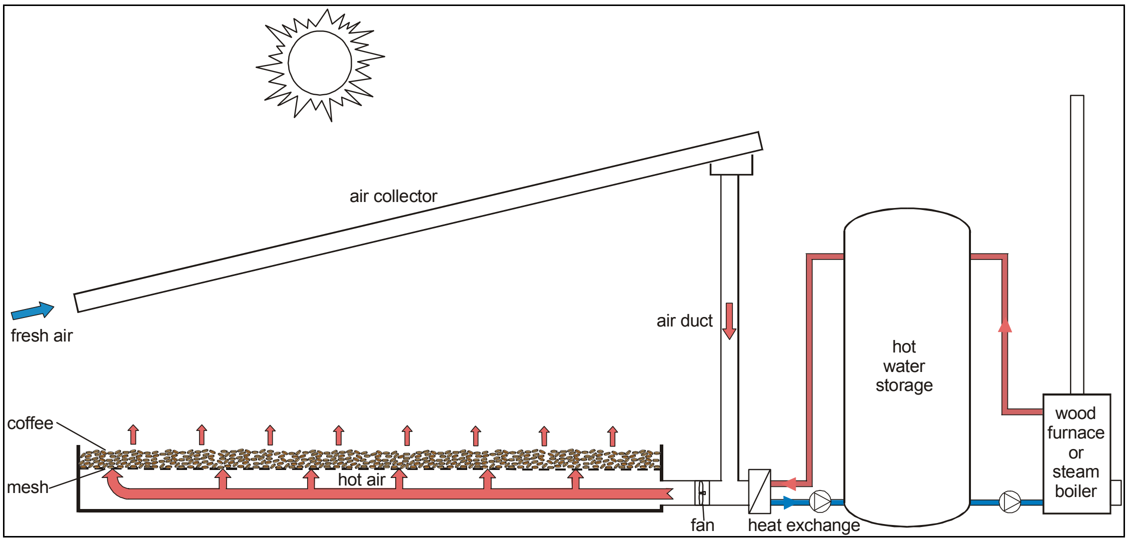


Fig. 47: Advanced solar coffee drying system using a wood furnace as back-up system. Due to the hot water storage, surplus heat from the wood furnace which can not be used instantly can be stored for later use.

6.2.2 Medium scale coffee drying in Kenya

Action is currently being taken in Kenya to improve the drying techniques for parchment coffee in smallholder co-operative factories. The Thailand Development Research Institute is responsible for the design, installation and commissioning of three drying installations based on a solar assisted drying process. The construction of the first of these was completed and commissioned at Rukera in November 1983.

The design of the dryer is shown in Fig. 48. The drying bins are contained in a building of which the roof forms a simple bare plate solar collector black painted corrugated iron with a hardboard ceiling suspended 30 cm beneath it. Air is drawn through the cavity between the roof and ceiling by means of a diesel-powered fan, the air being drawn also around the diesel engine block before entering the fan and being propelled into the drying bins. Temperature increases of up to 15 °C have been obtained by passage of air at 8.5 m³/s across the roof cavity, with an additional 3-4 °C increase derived from the waste heat of the engine.

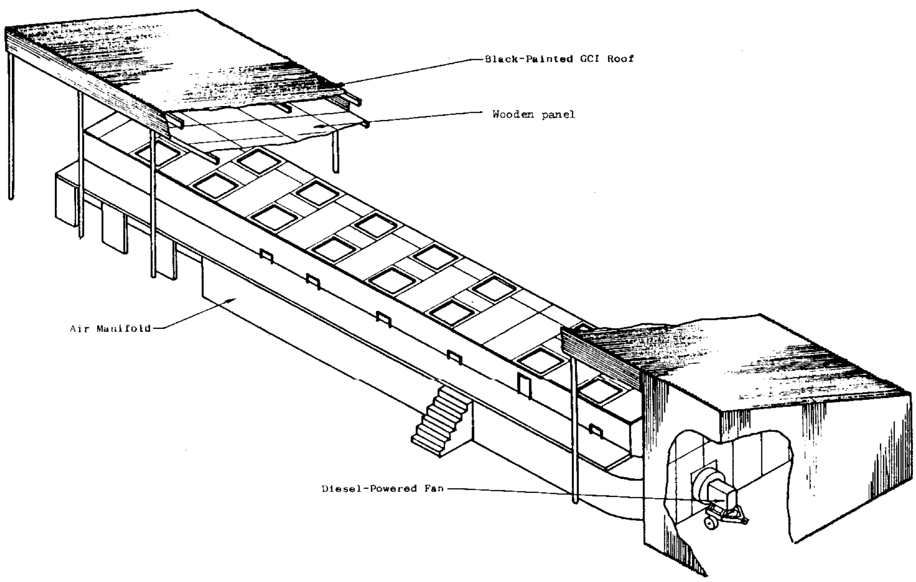


Fig. 48: Thailand Development Research Institute parchment coffee drying system. [38]

6.2.3 *Small scale coffee drying in Zimbabwe*

In co-operation of the Zimbabwe Coffee Grower's Association, Domestic Solar Heating, Pvt. Ltd. In Harare and AEE INTEC solar cabinet dryers have been developed for a farmers cooperative in the Honde valley in the east of Zimbabwe.
With the dryers the drying time could be reduced significantly and the quality of the coffee could also be improved.
To lengthen the operation time of the dryers and to reduce the pay-back time, they were designed in a way so that they can be used for coffee drying as well as for drying of bananas. In the case of coffee drying the bottom of the trays consist of a plastic net. If bananas are to be tried a plastic board is put on the net.

Fig. 49: PV-powered forced convection solar coffee dryer (left) and natural convection cabinet solar coffee dryer (right) at a farmers co-operative in the Honde valley, Zimbabwe

Fig. 50: Filling the trays with coffee

6.3 Grain Drying

For grain drying almost all active solar drying can be used. One of the most reported grain dryer design has undergone considerable development by the Asian Institute of Technology (AIT) in Bangkok, Thailand. It is shown in chapter 3.1.2 in Fig. 7.

Active cabinet solar dryer
A solar maize dryer incorporating a directly coupled photovoltaic (PV) powered DC fan was developed and field-tested for small scale use in Malawi, central Africa. The dryer has a capacity of 90 kg and it has been designed to utilise forced air circulation without the use of external power supplies like grid electricity, fossil fuel and batteries. A main design constraint was that the drying air temperature should not exceed 60°C, which is the international drying standard for maize grain used for human consumption. Temperatures in excess of 60°C lead to grain overheating, cracking and subsequent microbial attack. Results showed that the incorporation of a PV-driven fan provided some form of passive control over the air flow and hence the drying air temperature.

The dryer was coupled to a solar air heater having a sun-tracking facility and optimised blackened sisal rope grids for improved energy collection efficiency of the order of 80%. Grain drying with this solar dryer technology, compared with sun drying, reduced the drying time by over 70%. Grain quality, texture, and flour quality and flavour improved significantly with the dryer, as grain was permanently protected from sudden rains, vermin and dust contamination. Although the capital cost of the solar dryer was about US$900, the dryer was found to be cost-effective with a payback period of less than one year if it is used to dry grain for purchasing by the Cereal Boards [40].

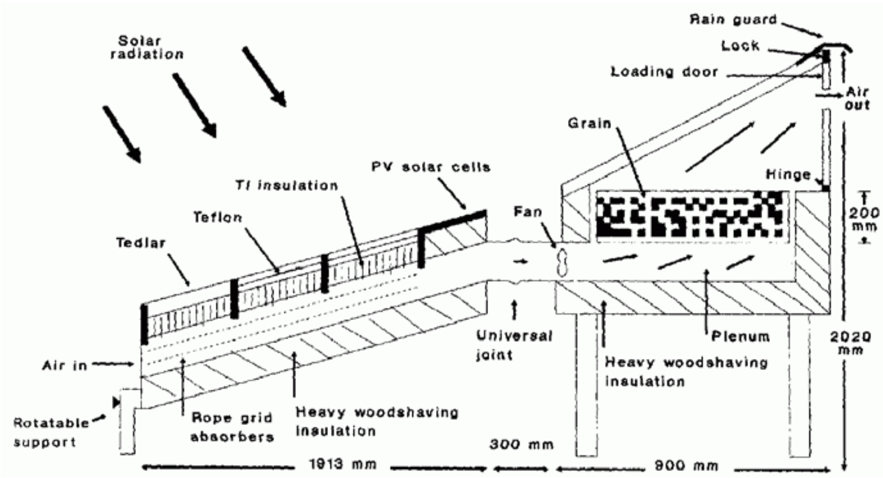


Fig. 51: Solar grain dryer with rotating indirect air heater and a photovoltaic DC-fan [40]

6.3.1 Grain specific considerations

6.3.1.1 Wheat

The most critical decision in harvesting is not the degree of mechanisation but the timing of the harvest. If the harvest starts late, the grain becomes too dry and rate of grain shattering is high. The longer a ripe crop is left in the field or on the threshing floor, the higher will be the loss from natural calamities including hailstorm, fire, birds, or rodents.
The moisture content of the grain will be high, making drying difficult if the harvest start too early.

The moisture content of wheat grain is a crucial factor from harvest until milling. Moisture content of 25 % is not uncommon in newly harvested grain in humid areas but it must be dried immediately to protect it against mould. At 14 % moisture grain can be safely stored for 2 to 3 months. For longer periods of storage from 4-12 months, the moisture content must be reduced to 13 % or below. [41]

6.3.1.2 Paddy

Field drying of the harvested paddy (rice), if it is not a shattering variety, should be practised moderately during the dry season only. If hand-harvested by sickle the grip size bundles are better laid out separated rather than stacked to achieve greater aeration rather than stacked. Stacking of moist paddy will cause heating up of the paddy, increasing the activity of micro-organisms and initiate a major deterioration in quality. A safe way is to thresh the paddy immediately after harvesting.
Two-stage drying consisting of flash or high-temperature short-exposure or fast drying to 18 % during the first stage and low-temperature and slow drying or sun drying to 14 % during the second stage is another technique to save a large volume of wet grain.
Paddy at 18 % moisture content can be stored for two weeks. However, re-wetting of the grain should be avoided to prevent cracking or fissuring which will have telling effects in milling. [42]

6.3.1.3 Parboiled paddy

After parboiling, paddy contains about 35% moisture. During the parboiling process the starch is gelatinized which confers quite different drying properties to that of field paddy. It has been shown that in the drying of parboiled paddy, significant damage (i.e. kernel cracking) does not occur until the moisture content falls to 16%, regardless of the drying method or the rate of drying. Cracking then occurs some time after the grain has cooled. The recommended drying procedure is to dry the parboiled paddy to 16-18% moisture as fast as facilities permit, temper it for four hours if warm or eight hours if cooled, and then dry in a second operation to 14% moisture. Air temperatures of 100-120°C can be used for parboiled paddy in continuous-flow dryers.[43]

6.3.2 Drying of Seed Grain

If grain is destined for use as seed then it must be dried in a manner that preserves the viability of the seed. Seed embryos are killed by temperatures higher than 40-42°C and therefore low temperature drying regimes must be used. Seed grain may be dried in any type of dryer provided that it is operated at a low temperature and preferably with higher air flowrates than generally used. It is essential that batches of grain of different varieties are not mixed in any way and therefore the dryers and associated equipment used must be designed for easy cleaning. In this respect simple flat-bed dryers are more suitable than continuous-flow dryers.

TETER [45] noted that seed paddy can be sun dried at depths of up to 30 mm but that the final stages of drying to 12 % moisture should be conducted in the shade to avoid overheating and kernel cracking. Flat-bed dryers can be used with bed depths of up to 0.3 m, air temperatures not exceeding 40 °C, and airflows of 1.3 - 1.7 m^3/s per tonne of grain.

Cross-mixing between batches of different varieties can be avoided by drying in sacks in a flat-bed dryer although care must be taken in packing the loaded sacks in the dryer to ensure reasonably even distribution of airflow. Specialised tunnel dryers in which sacks or portable bins are individually placed over openings in the top of the tunnel have been developed [45].

6.3.3 Technical aspects of grain drying

6.3.3.1 Resistance to Air Flow

The energy required to force air through a bed of grain is dependent on the air flow, the grain depth and physical properties of the grain such as surface and shape factors, the kernel size distribution, moisture content, and the quantity and nature of contamination, stones, straw, weeds etc.
The relation between air flow and the pressure drop generated across the bed for selected grains is illustrated in Fig. 52. The data generally refer to clean and dry grain and correction factors of up to 1.4 are used for very wet and dirty grain. [45]

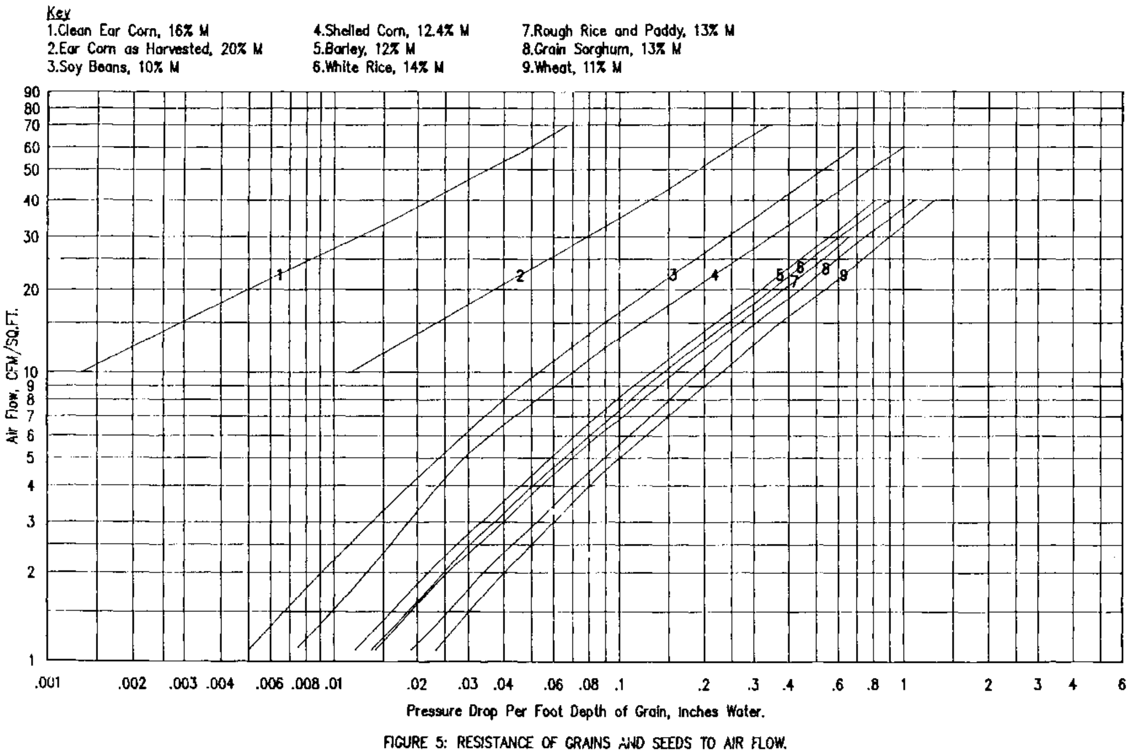


Fig. 52: Resistance of Grains and Seeds to Air Flow [43]

6.3.3.2 Latent Heat of Vaporization

Energy in the form of heat must be supplied to evaporate moisture from the grain. The latent heat of vaporization, L, for a grain depends on its moisture content and temperature and is appreciably greater than the latent heat of evaporation of water. The latent heat of vaporization for paddy at selected moisture contents and temperatures is shown in Table 10. Data for other grains have been reported by [46].

Table 10: Latent heat of vaporization of paddy

Temperature [°C]	Latent Heat of Vaporization [kJ/kg]					
	Free Water	Moisture Content %(wb)				
		14	16	18	20	22
25	2,443	2,605	2,518	2,483	2,464	2,453
30	2,431	2,593	2,506	2,471	2,452	2,441
35	2,419	2,580	2,493	2,458	2,440	2,429
40	2,407	2,567	2,482	2,447	2,428	2,417
45	2,395	2,555	2,469	2,434	2,416	2,405
50	2,383	2,542	2,456	2,422	2,404	2,393
55	2,371	2,529	2,444	2,410	2,391	2,381
60	2,359	2,516	2,432	2,398	2,379	2,369

In the drying of grain in a deep bed, whilst individual kernels may all be losing moisture at different rates, the overall drying rate will remain constant for a long period. The air absorbs moisture as it moves through the bed until it becomes effectively saturated and moves through the remaining layers of grain without effecting further drying.

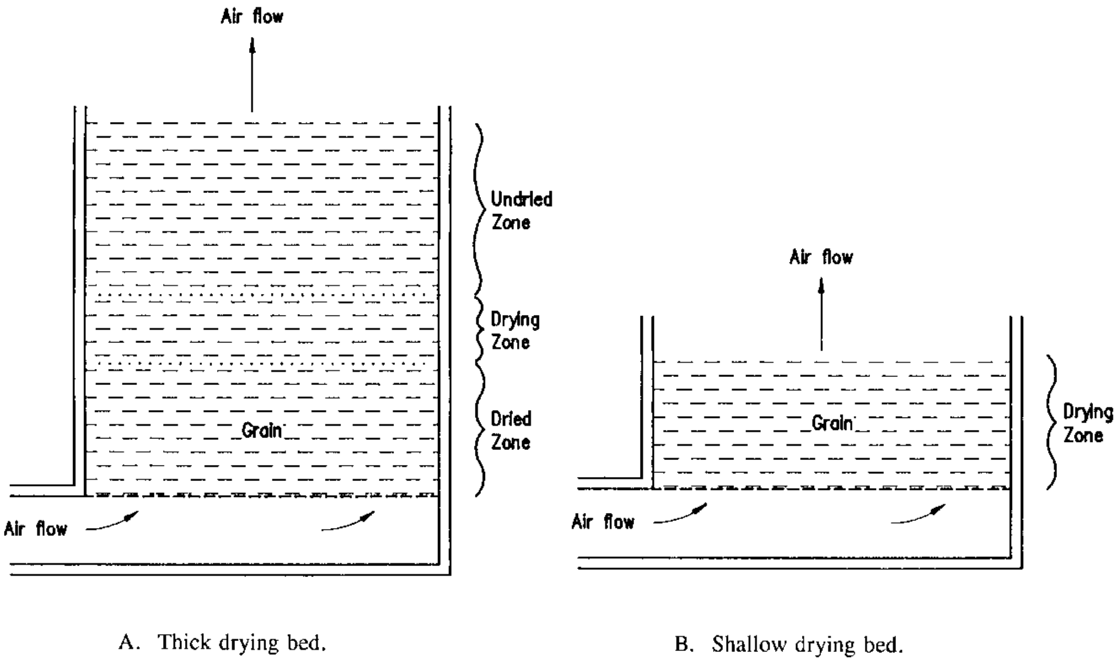


Fig. 53: Drying zone in fixed-bed drying.

Fig. 53 shows the three zones present within a thick drying bed at an intermediate time within the drying operation. Drying takes place within a discrete zone, the size of which depends on the moisture content of the grain and the temperature, humidity and velocity of the air. Below the drying zone is the dried zone where the grain is in equilibrium with the air. Above the drying zone is the un-dried zone wherein the grain remains unchanged from its initial condition. In a shallow bed as in Fig. 53B the drying zone is thicker than the bed depth and drying would occur initially throughout the bed.

The change in temperature and humidity of air as it moves through a bed of grain depends on the rate at which moisture is being evaporated from each kernel as an individually exposed element. Knowledge of the effect of grain moisture content, other grain properties, the temperature, humidity and flow rate of the air upon fully exposed kernels is essential to an understanding of how drying would proceed within a bed.

Comprehensive data on the numerous physical and thermal properties of grain are available in publications such as [46, 47].
Experiments and simulations to evaluate the drying rates for deep bed drying of maize in a natural-convection dryer have been developed by SIMATE [48]; for paddy by BALA & WOODS [49] and BASUNIA & ABE [50].

6.4 Timber Drying

The production of high quality timber from hardwood for the furniture and building industry requires a gentle and controlled drying to a moisture content of 8 to 15 % d.b.. Ambient air drying is dependent on weather conditions which leads to an extended drying period of ½ to 2 years and frequently causes quality losses.

Depending on the species of wood and the thickness of boards conventional high-temperature drying reduces the drying time to 2 to 8 weeks, but also requires high investment and causes high energy costs.

6.4.1 Large scale greenhouse type solar dryer

There are many different designs for large scale drying of timer in greenhouse-type solar kilns; Fig. 54 illustrates four of them.

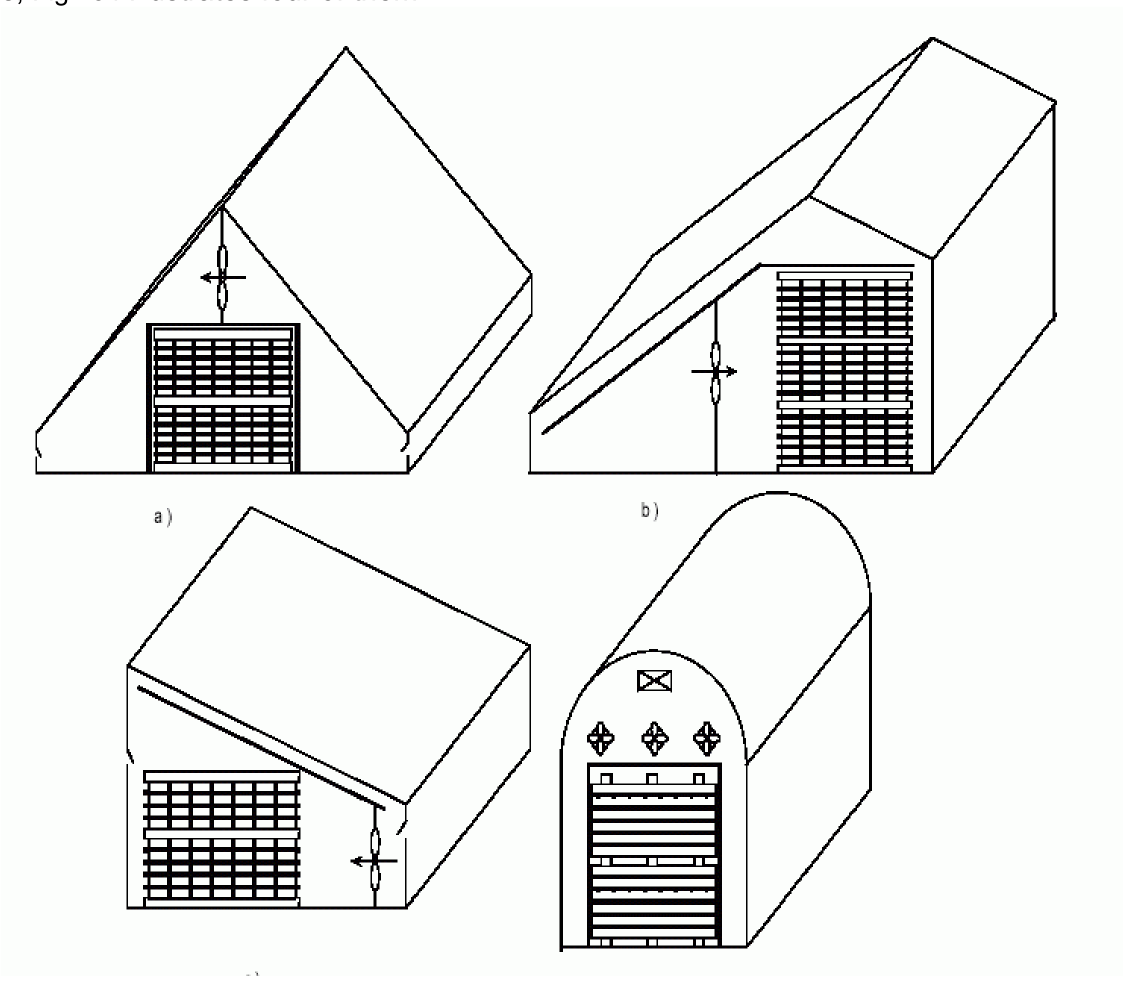


Fig. 54: Different types of large scale greenhouse solar kilns.

For a controlled drying of 100 to 240 m³ of timber per load the following design was developed by [51]. The substructure of the dryer is covered with a transparent, highly UV-stabilised and well isolating air bubble foil. A horizontal absorber made of black coated aluminium sheets separates the attic from the drying chamber. A specially developed microprocessor control regulates several axial flow fans, a humidifier and a back up wood chip furnace, providing the heat during night and unfavourable weather conditions. The drying regime is adjusted automatically according to the type of wood, the board thickness and the ambient air temperature. The modular design of the dryer allows an adaptation of the capacity to the needs of the user.

In co-operation with the Brazilian company *CAF Santa Barbara Ltd.* worlds largest solar drying plants were built up in the states of Minas Gerais and Bahia, drying up to 35,000 m³ of eucalyptus annually. With the developed low temperature drying regime even the Brazilian eucalyptus wood which is up to now mainly used for charcoal production, fuel and pulp for paper industry can be dried to a high quality product for the furniture and building industry. The investigations showed that investment, drying cost and energy consumption could be reduced by 40 to 60 % compared to conventional high-temperature drying systems. The introduction of this sustainable and environmentally friendly technology can contribute considerable to the use of regrown plantation wood and by this the protection of natural forests.

6.4.1.1 Design and operation

According to the above mentioned objectives, a solar assisted dryer for timber was developed. In order to minimize the construction cost of the drying chamber the required substructure is based on a greenhouse construction with vertical side walls and a ridge roof, Fig. 56.

The structure consists of rectangular aluminum profiles which are corrosion-resistant. The drying chamber is 10 m wide and up to 20 m long. The side walls are 3 to 4 m in height and the roof is inclined at an angle of 22 degrees. To adapt the drying capacity to the requirements of the user, the drying chamber is designed in a modular system allowing the length of the dryer to be expanded in segments of 2 m. Each segment is covered with a transparent highly UV-stabilized PE-EVA air bubble foil, providing a transmittance of 83 % for direct and 68 % for diffuse radiation. A weather strip, welded along both sides of the 2 m wide foil sheets, is pulled into fastening profiles which are fixed on the girders by self drilling screws Fig. 57.

The gable ends of the drying chamber are covered by polycarbonate double-skin sheets. For loading and unloading the dryer two revolving doors are installed over the full width of the drying chamber at the front side.

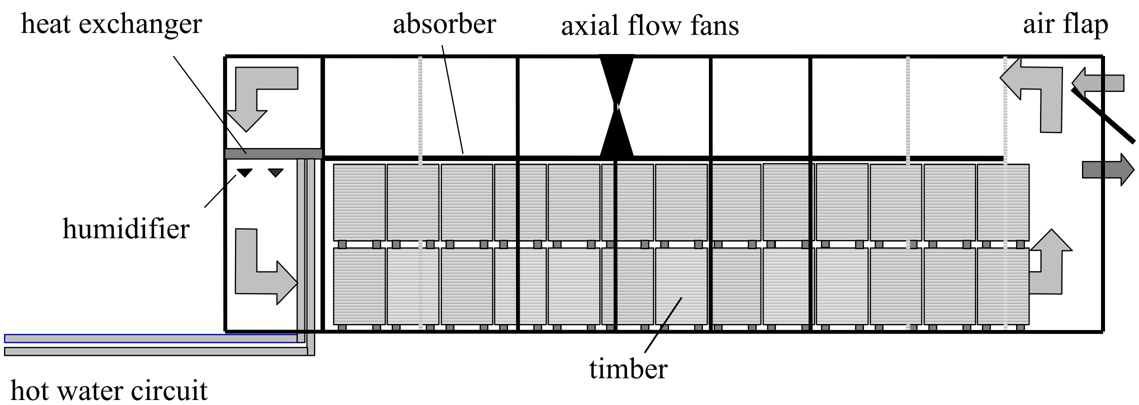


Fig. 55: Longitudinal section of the solar-assisted drying kiln.[51]

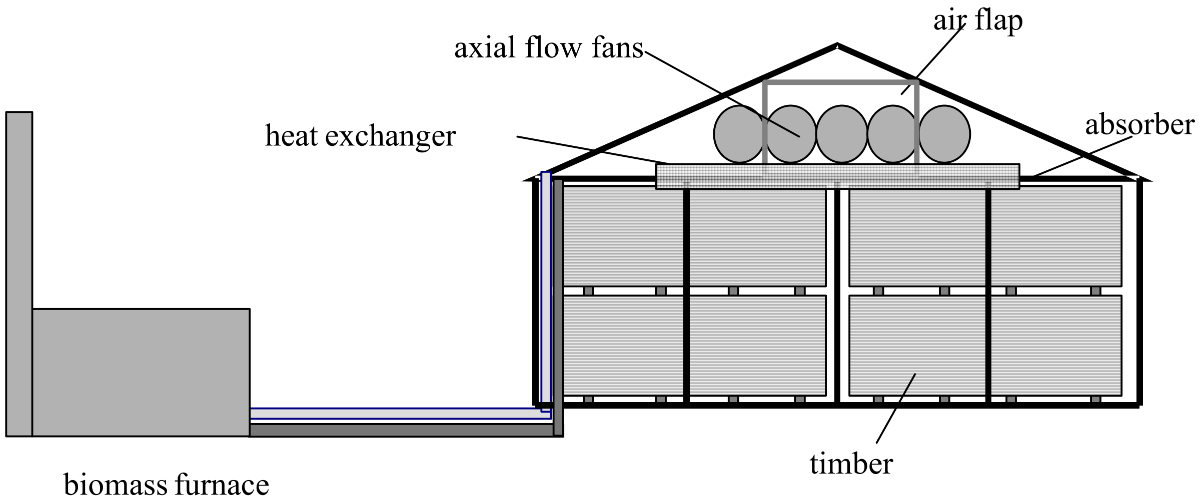


Fig. 56: Cross section of the solar-assisted drying kiln. [51]

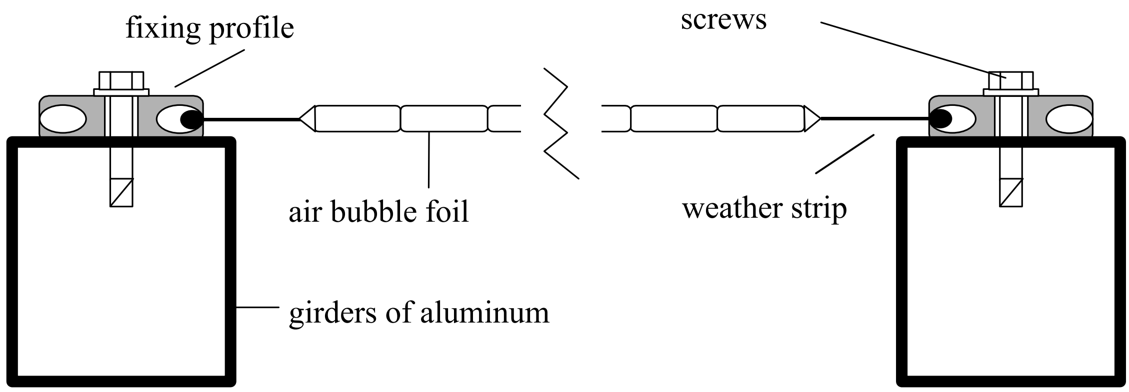


Fig. 57: Cross section of the fastening system for air bubble foils [51]

Due to the extremely high mechanical strength of the foil it can withstand wind speeds of up to 140 km/hr without any risk of damage. Based on experiences gained under moderate climatic conditions a life span of the foil of at least 10 years can be expected even under tropical conditions. The low heat transfer coefficient of the air bubble foil and the polycarbonate double-skin sheets of 3.2 W/m^{2}K reduce heat losses and prevents condensation at the inside of the cover during the drying process. This gives the air bubble foil priority over other transparent cover materials such as single layer PE-foil or even glass.

To convert solar radiation into heat, black coated aluminium sheets are installed horizontally in height of the eaves separating the drying chamber from the attic. The suspended plate absorber in combination with the corrugated surface causes an excellent heat transfer to the drying air.
The boards or beams are stacked underneath the absorber taking up the whole space between the ground and the absorber plate. Vertical foils installed between the side walls and the piled timber prevents undesired air flow without passing the boards or beams.
In the middle of the attic five speed controlled axial flow fans with a maximum power consumption of 1.6 kW each provide a total air flow rate of up to 125 000 m^3/h. The fans ensure a permanent airflow, which circulates inside the kiln passing the clearance between the boards in horizontal direction. The air velocity in the open space ranges from 1.5 to 2.5 m/s depending on the rotation speed of the fans.

The drying air is heated at the absorber surface during sunny weather. The heat required during the night and adverse weather conditions is provided by a supplementary heating system. A highly efficient biomass furnace operated with wood chips generates hot water at a maximum temperature of up to 85 °C. The heat is converted to the drying air by a heat exchanger with a maximum heating capacity of 200 kW. The heat exchanger is installed horizontally in the height of the eaves at the back side of the drying chamber. Underneath the heat exchanger a two-stage humidifier is installed consisting of 16 equally distributed spraying nozzles for water.

At the front of the drying chamber a motor controlled recirculation flap is incorporated into the gable regulating the air exchange with the ambient in dependence on the desired humidity and temperature. Sensors for temperature and relative humidity are installed inside and outside the plant. Furthermore, the water content of the timber is measured continuously at 5 different positions in the load All components and sensors are controlled by a microprocessor-based, menu-guided controlling system.

6.4.1.2 Energy Consumption

The newly developed low-temperature drying regime shows a significantly lower electrical and thermal energy consumption in comparison to conventional high-temperature drying systems as indicated in Table 11.

Table 11: Comparison of power input, electrical and thermal energy consumption of the solar-assisted timber dryer in comparison to conventional high temperature drying systems based on drying of 27 mm thick eucalyptus grandis boards from 60 to 11 % d.b.

	Conventional*	Solar**
Installed electrical power, W/m^3	100 – 250	< 50
Installed thermal power, kW/m³	2 - 5	0,9
Electrical energy consumption, kWh/m³	60 - 100	20 - 40
Thermal energy consumption, GJ/m³	3 - 4	1 - 2

* Brunner-Hildebrand GmbH, Germany 1996, Gloor Engeneering GmbH, CH 1996; ** CAF Sta. Bárbara Ltda, Brazil 1997

As indicated in Table 11 the thermal and the electrical energy consumption of the solar drying plant is considerable lower compared to the energy consumption of conventional kilns. Therefore the fuel consumption and the size of the back-up furnace in the solar assisted dryer can be reduced by almost 50 %. Due to the comparatively high irradiation in Brazil about 30 to 40 % of the thermal energy consumption were covered by solar energy. Furthermore, there is no need for hot water temperatures of more than 85 °C since the drying temperatures are below 60 °C. Therefore, a pressurised boiler or steam system which is normally used for conventional kilns is not required for the solar drying plant, reducing the investment, the supervision and the statutory regulations.

In addition, the electrical energy consumption is reduced by 50 %, since the length of the piled timber is higher than in conventional kilns. Furthermore the relatively low air speed during the drying process causes a low pressure drop of less than 50 Pa and allows the use of highly efficient axial flow fans.

6.4.1.3 Drying Costs

Based on the investigated data of several commercially operated solar drying plants and commercial offers of the most important national and international manufacturers of conventional drying kilns the drying costs were analysed, Table 12. The study showed that under Brazilian conditions the required investment for the solar drying plant was approximately one half of the investment necessary for a conventional dryer with the same drying capacity. The cost analysis includes the complete system with the dryer, the biomass furnace, the civil construction and the installation.

Since the drying time of eucalyptus species in the solar dryer is only 20 to 30 % longer than the time required for drying in a sophisticated conventional kiln, the lower investment and the reduced energy consumption results in a reduction of the total drying costs by 40 to 50 %.

Table 12: Comparison of drying costs of 27 mm boards of *eucalyptus grandis* from green to 11 % moisture content in a solar assisted dryer and a conventional high-temperature dryer based on prizes in Brazil in 1999

	Conventional*	**Solar****
Drying time, d	15 - 25	22 - 30
Total Investment**, US$/m³	800 - 1000	400 - 500
Energy cost, US$/m³	6 - 12	3 - 6
Depreciation/Capital cost, US$/m³	10 - 12	5 - 8
Total cost***, US$/m³	20 - 30	12 - 15

* *E.grandis* from green (X=60-80%) to X=11 %; ** dryer and furnace including civil construction and installation; *** Costs for capital, energy, depreciation and repairs

Investigations on drying regimes for thicker boards and mixed assortments, other species, moderate ambient conditions and a simulation program for a further optimisation of the solar drying plant are in development.

6.4.2 Small scale greenhouse timber dryer

The following greenhouse kiln incorporates a solar air collector into the structure of the kiln chamber. The kiln itself may be constructed of framing lumber with plywood sheeting or bay be block or other similar construction. The kiln must have a well insulated floor, preferably with a drain of some sort to remove condensation from inside the kiln. All non-collector surfaces must be well insulated. As rule of thumb for every 10 board feet of lumber one square foot of glazing material is needed [52]. It is very important to maintain air flow through the lumber piles during drying. The moisture exits through vents to the outside or condensates at the side walls and runs of in a drain. An obvious way of increasing the volume of lumber dried per year is to load the dryer with air-dried stock.

In an ultra simple solar process the air drying stacks are simply wrapped in plastic sheets. Humidity is kept high as moisture gradually diffuses out of, or condenses onto the plastic in a kind of hot house environment.

Simple solar kiln design for the use in high latitudes is described by Yang (1980). Fig. 58 shows a cross section of this dryer. A detailed review of solar wood drying has been prepared by Steinmann (1989), who made detailed measurements and simulations of drying timber in an kiln that is similar to that of Fig. 59.

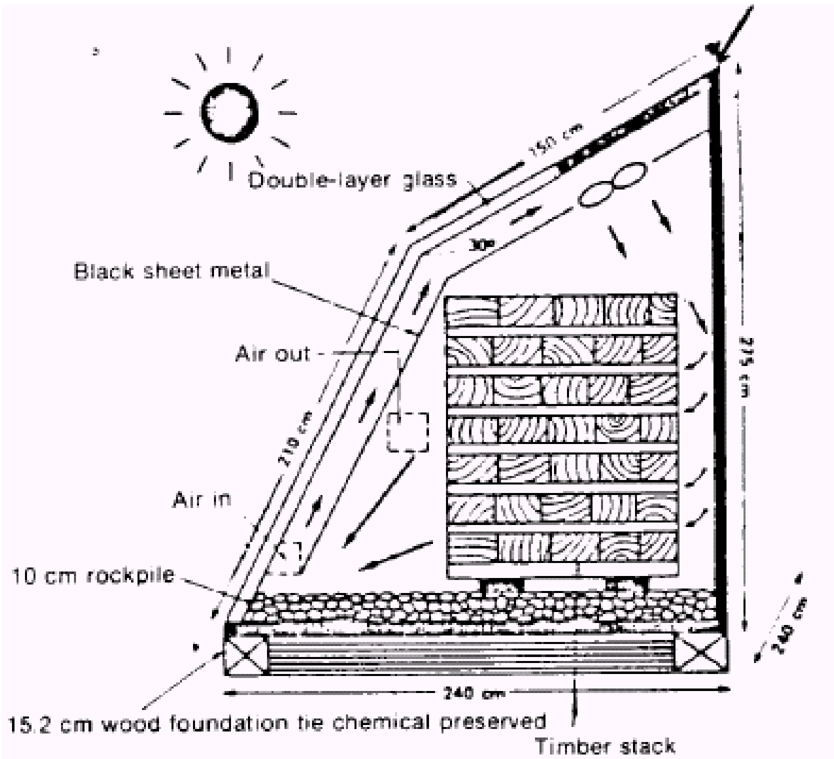


Fig. 58: Cross section of a solar timber dryer at Thunder Bay [53]

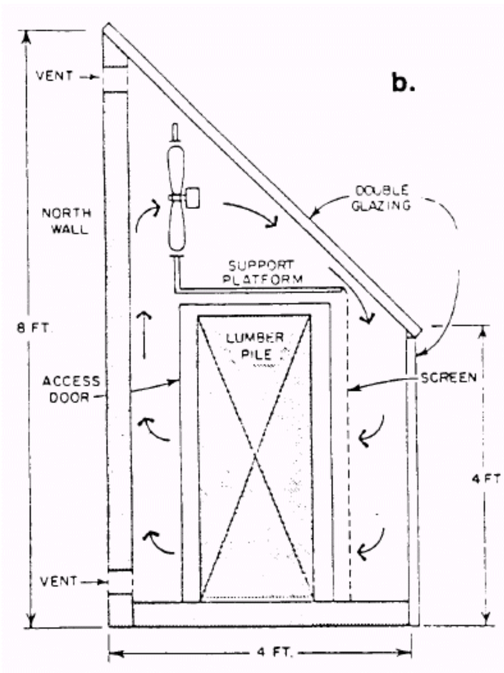


Fig. 59: Cross section of a simple greenhouse type timber dryer [54]

Depending on thickness of lumber, the design [55] illustrated in Fig. 60 has a capacity of 750 to 850 board feet of 8-foot lumber. The dryer is of all wood construction and insulated. Insulation pads can be tacked to walls and ceiling. The south side of the dryer is enclosed with four storm windows of single-strength glass, giving a glass area of about 4.3 m². The south wall slopes 40° from the vertical and each solar-collecting unit has been rotated slightly in an effort to catch some early morning and late afternoon sunshine. This latter detail may be of questionable benefit and may be considered an optional construction detail.

Two vents in the floor are covered with hardware cloth to keep out rodents. These floor vents are each 10 cm x 25 cm and located under the central plenum. The overhead fans (two spaced evenly over the 8-foot dryer load) each deliver 34 m^3/min downward between the two lumber stacks. Hinged baffles hanging from the fans insure that all air delivered by the fans is directed between the stacks into the “plenum” space so that all available air delivered circulates through the sticker-separated lumber. Plenum space should be 40 to 50 cm wide to insure uniform air distribution through the lumber. The electric fans are activated by a thermostat which is set to turn fans on when the inside temperature reaches 26 °C. The window glass units face dull black painted sheet metal and hardboard-backed solar collector units. The top and bottom of each collector unit are open to allow circulation of the heated air. A side door on the east side of the dryer provides loading and unloading access and permits inspection of the lumber. An adjacent smaller door serves as access to the solar-heating area. The dryer is mounted on treated wood foundation posts set 0,75 m in the ground.

The dryer will bring lumber down to about 8 percent moisture content in time; the time determined by initial moisture content of the lumber, time of year, and species being dried.

The manner in which the dryer works is as follows: the sun’s rays pass through the glass and a portion of the available heat is absorbed by the black metal heat collector. The metal in turn heats the air space within. When the fans are in operation, the heated air is circulated through the lumber picking up moisture. Some air is admitted and vented in the process through the floor slots, the necessary amount depending on the moisture content in the dryer. When moisture-laden green lumber is being dried, vents may be left full open; as lumber becomes dryer, vents may be gradually closed. The purpose of venting is to keep the relative humidity of the air in the dryer as low as possible while maintaining a high dry-bulb temperature. When the thermostatically controlled fans are not operating, collectors and some drying still takes place as air moves slowly through the dryer by natural convection.

It is important that the lumber be stacked properly with uniformly sized 3/4-inch (or thicker) dry stickers separating each course of lumber. Each tier of stickers should be aligned carefully, about 24 inches apart for hardwoods. Further details on good stacking principles are described in the “Air Drying of Lumber, A Guide to Industry Practices,” Agriculture Handbook No. 402, USDA, Forest Service, which is available from the Superintendent of Documents, Government Printing Office, Washington, D.C.

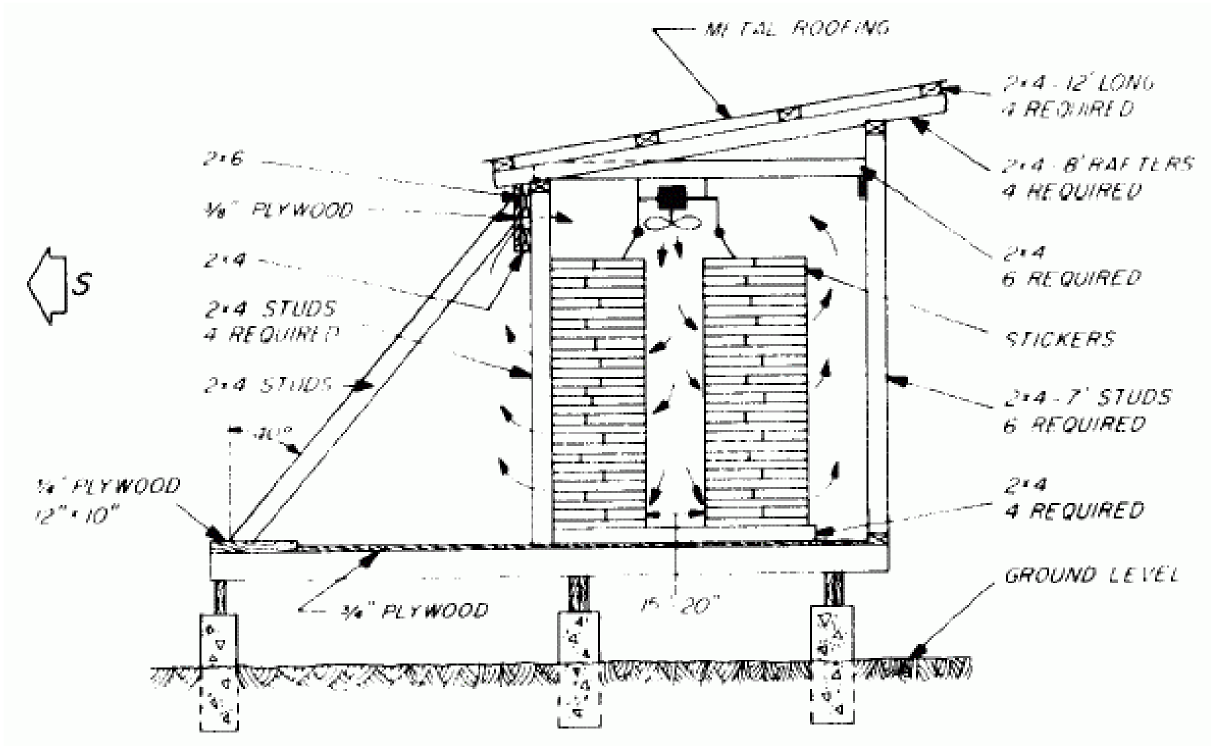


Fig. 60: Drawing of dryer construction details with stacked lumber charge in place. Arrows indicate movement of air through lumber. Heat from collector area on left is circulated forcefully by overhead fans. [55]

Solar kilns with external solar air collectors can be very sophisticated with thermostats controlling dampers that can shut off the ducts to avoid too high temperatures inside. So they offer greater control of the drying process and better efficiency than greenhouse kilns but they are more expensive to build and require some engineering knowledge to design.

6.5 Tobacco Curing

For curing of wrapper tobacco, which represents the most delicate type of primed cigar tobacco, a solar assisted dryer based on a standard greenhouse structure was developed by [7]. Due to the sophisticated climatic control of this special solar dryer it can be adapted for drying other products like timer or bricks.

6.5.1 Greenhouse type tobacco dryer

The solar assisted greenhouse type dryer basically consists of a plastic film greenhouse, which is 10 m in width, 16 m in length and 6.6 m in height, a solar air heater incorporated in the roof, a humidifier, a supplementary biomass furnace, a heat exchanger and four axial flow fans. Inside the solar barn, horizontal beams are placed n five different heights to serve as rack for the tobacco leaves.

A black absorber tissue is mounted below the girders. It serves in a dual function, both as shade for the tobacco leaves and as aperture for absorbing solar radiation. The axial flow fans, each of 500 W power consumption, are installed in an air conditioning unit at one of the gables to blow air in the attic. Three of these fans ensure a permanent supply of circulating air. The collector fan is forcing air through the absorber tissue for heat transfer when thermal solar energy is available and needed. The circulating air passes downwards through the tobacco leaves in vertical direction and is finally forced back over the ground to the air conditioning unit. As a result of the upside down air flow, warm and dry air enters the attic, preventing condensation of water on the cold roof during night time. A supplementary firewood furnace of 80 kW calorific power, with a hot water circuit and a heat exchanger installed in the air conditioning unit, maintains the optimum temperature during night or periods of low radiation. To provide sufficient humidity even at varying temperatures, a humidifier is integrated into the system.

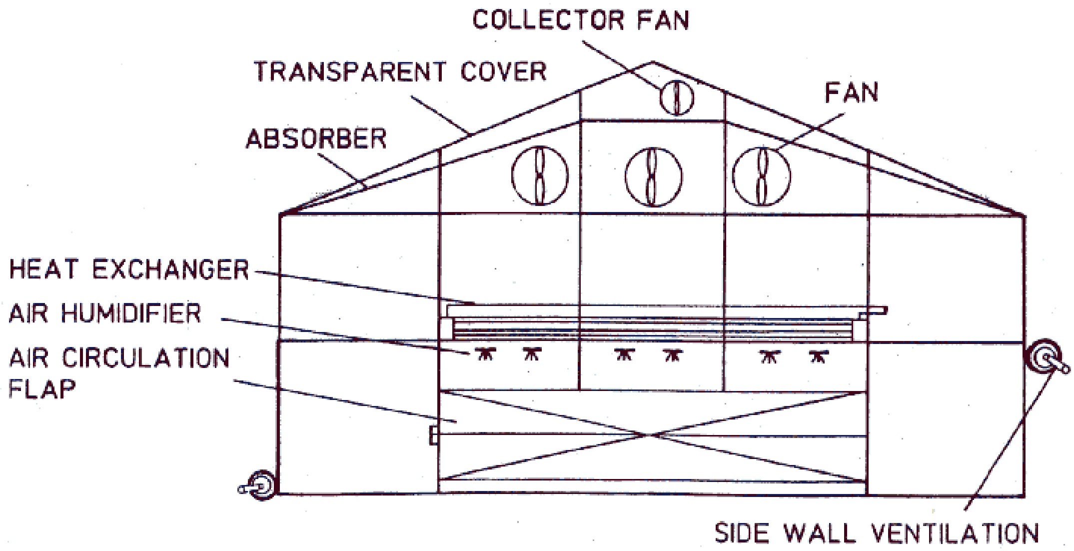


Fig. 61: Cross section of the solar heated curing barn for tobacco.

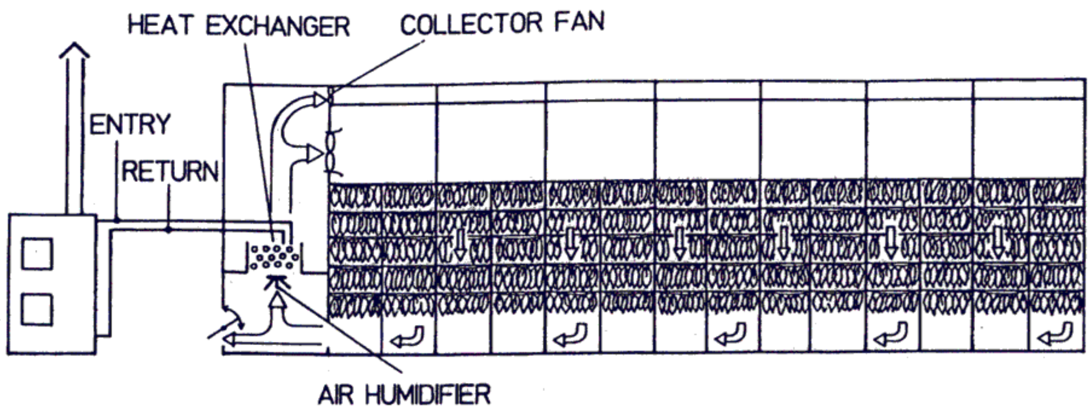


Fig. 62: Longitudinal section of the solar heated curing barn for tobacco.

Humidity is controlled by means of a recirculation flap incorporated into the gable. In recirculation mode the flap is closed and the air is circulated in the barn. During this mode of operation the humidity rises and fresh air has to be mixed in certain amounts. In ambient air mode, the flap is completely opened and only ambient air is sucked. Since the water content of the ambient air is generally lower than the water content of the re-circulated air, the humidity decreases if temperature is kept constant. Via electronic control of the recirculation flap, any ratio of fresh and circulating air can be adjusted in order to provide the required curing conditions. Thus, curing in the solar bam is widely independent of weather conditions.

In a high efficient down draught firewood-furnace water is heated and pumped to an isolated heat storage tank or to the heat exchanger inside the air conditioning unit of the solar barn. The calorific power of the furnace is controlled thermostatically via regulation of the combustion air fan. Individual regulation of the primary and secondary air and the division of drying, gasification and burning zone ensures an efficient combustion and low emissions. A reservoir for 200 kg of firewood provides sufficient fuel for at least 10 hours of operation.

The use of the solar assisted greenhouse type dryer for curing of wrapped tobacco in Brazil showed several advantages compared to the traditional curing method. Curing in the sensor controlled solar barn allowed the use of higher temperature to accelerate the biochemical processes without the risk of drying the tobacco too fast. Thus, the curing process could be finished after 15 to 20 days without any impacts on quality, while conventional curing took 30 to 40 days. Furthermore, the forced air circulation in the solar barn allows a closer spacing of the leaves facilitating a bulk density of 20 kg/m³ compared to 4 - 5 kg/m³ in the conventional barns. This results in a reduction of the required barn capacity from 122 to 17 m³/ha. The firewood consumption can be reduced from 30 to 2 kg per kg dried tobacco. Usual leave losses by barn rots from 4 to 10 % could be reduced considerably to less than 1 %. The economic viability of the system was confirmed by an economic feasibility study, the solar curing barn proved to be a promising alternative to traditional tobacco curing and wood processing systems[1].

6.5.2 Solar assisted conventional tobacco curing

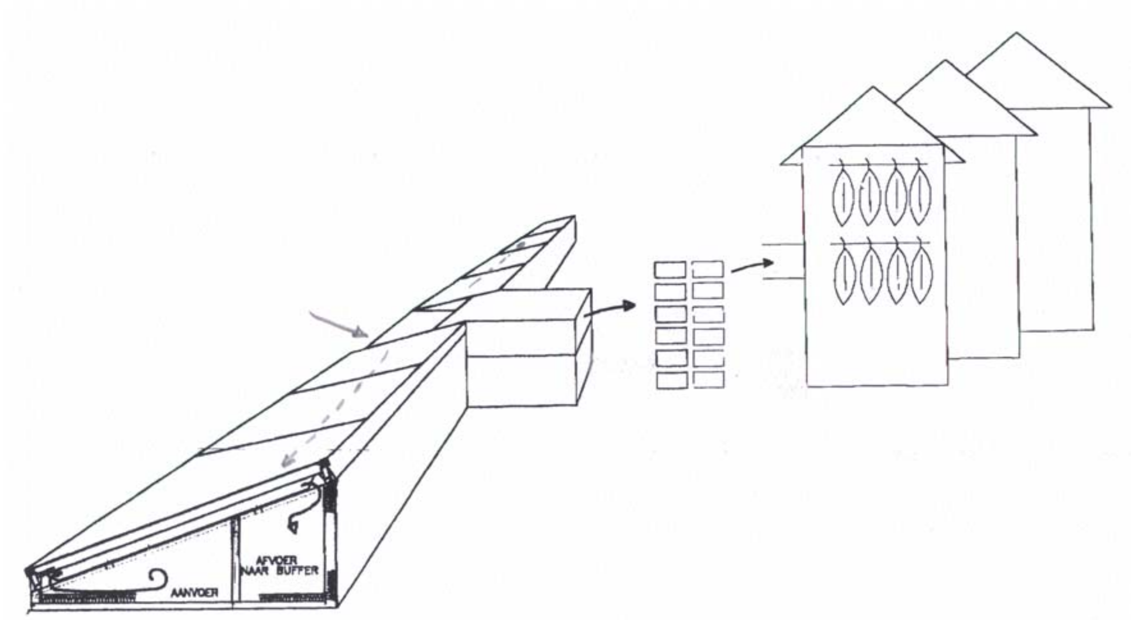


Fig. 63: Tobacco curing – direct connected air based system [36]

[1] BUX, MÜHLBACHER (2002)

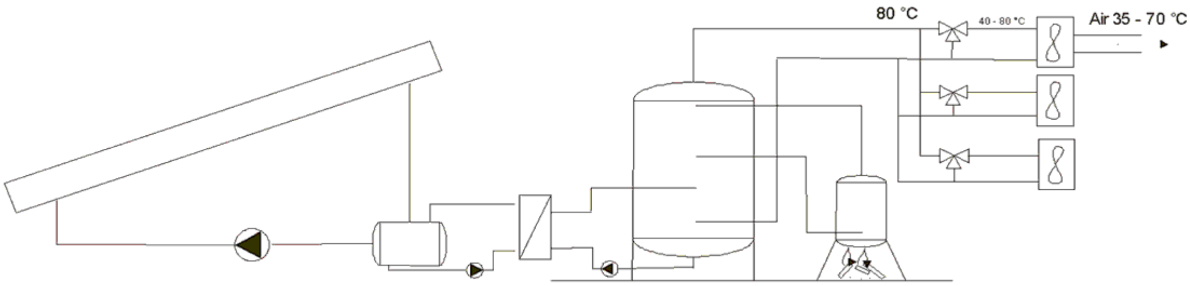


Fig. 64: Tobacco Curing - Water based system with pump circulation [36]

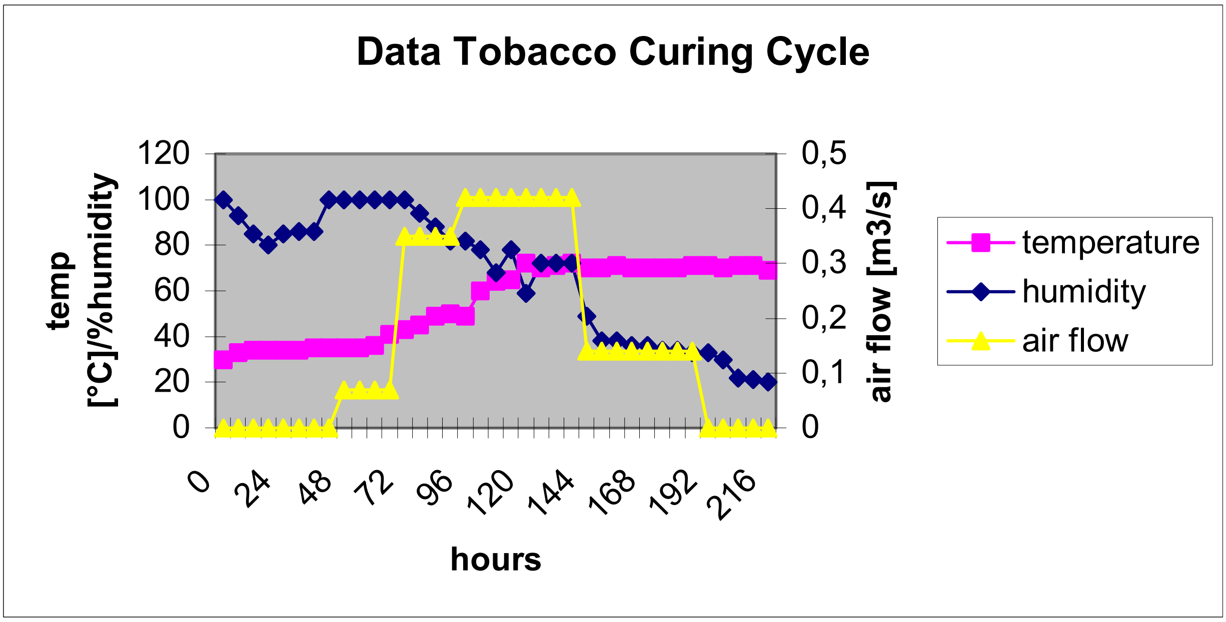


Fig. 65: Data of a tobacco curing cycle [36]

6.6 Fish Drying

Drying is the traditional method of preserving fish. Fresh fish contains up to 80% of water and it is a highly perishable material. When moisture content is reduced to 25% (w.b.), contaminating agents can not survive and autolytic activity is greatly reduced. However, to prevent mould growth during storage, moisture contain must be reduced to 15%. Tropical species of fish can generally withstand temperatures of 45 to 50 °C before proteins are denatured or cooking starts. [49]

Fig. 66: Kapenta drying at lake Kariba, Zimbabwe

6.6.1 Tunnel dryer

The Hohenheim tunnel dryer (see Chapter 4.4) can also be used for drying of fish. In Bangladesh 150 kg of Silver Jew (*Johnius argentatus*) fish were dried from 66 % w.b. down to 16 % w.b. in 5 days. Comparable samples dried with the traditional methods had a moisture content of 32.84 % w.b. after 5 days. The temperature of the drying air at the collector outlet varied from 35.1 °C to 52.2 °C during drying. The fish was initially treated with dry salt and stacked for about 16 hours before drying.[49]

7 Components

7.1 Air collectors

The solar air collector is designed to heat air when irradiated by the sun. The basic components are: cover, absorber, air passage and insulation. Solar radiation transmitted through the cover heats the absorber, which in turn heats the air in the air passage.
The information provided in the following chapters are mainly results of Task 19 on Solar Air Systems of the IEA's Solar Heating an Cooling Programme [56, 57].

7.1.1 Advantages and disadvantages of air collectors in comparison to water collectors

+ Air will not boil, cannot freeze and no damage results when there is a leakage.
+ Nearly no corrosion problems.
+ The system will not malfunction if there are small leaks.
+ Air is non-toxic (at least, no more toxic than the air we breathe) and is freely available anywhere and at any time.
+ Well designed solar air heating systems require less technical equipment than water-based systems.

- Low heat capacity of air
- High volume flow-rates, big duct-dimensioning
- Low heat transfer between absorber and air
-

7.1.2 Typology

A general typology for air collectors can be defined according to their subelements in the following way.

Absorbers:

- Non-permeable:
  - Underflow
  - Underflow with ribs in air flow
  - Overflow
  - Under- and overflow
- Permeable:
  - Glazed matrix (metal or cloth)
  - Perforated metal, unglazed
- Window collector:
  - Alternate functions-direct grain with daylighting or collecotors
- Hybrid (air / water):
  - Both air and water from the same absorber
- Hybrid (air / photovoltaic):
  - Both air and electricity from the same absorber

Absorber coatings:

- Selective
- Non-selective

Glazing:

- Single
- Double
- Unglazed

Production
- Ready made modules
- Site assembly of semi-finished products

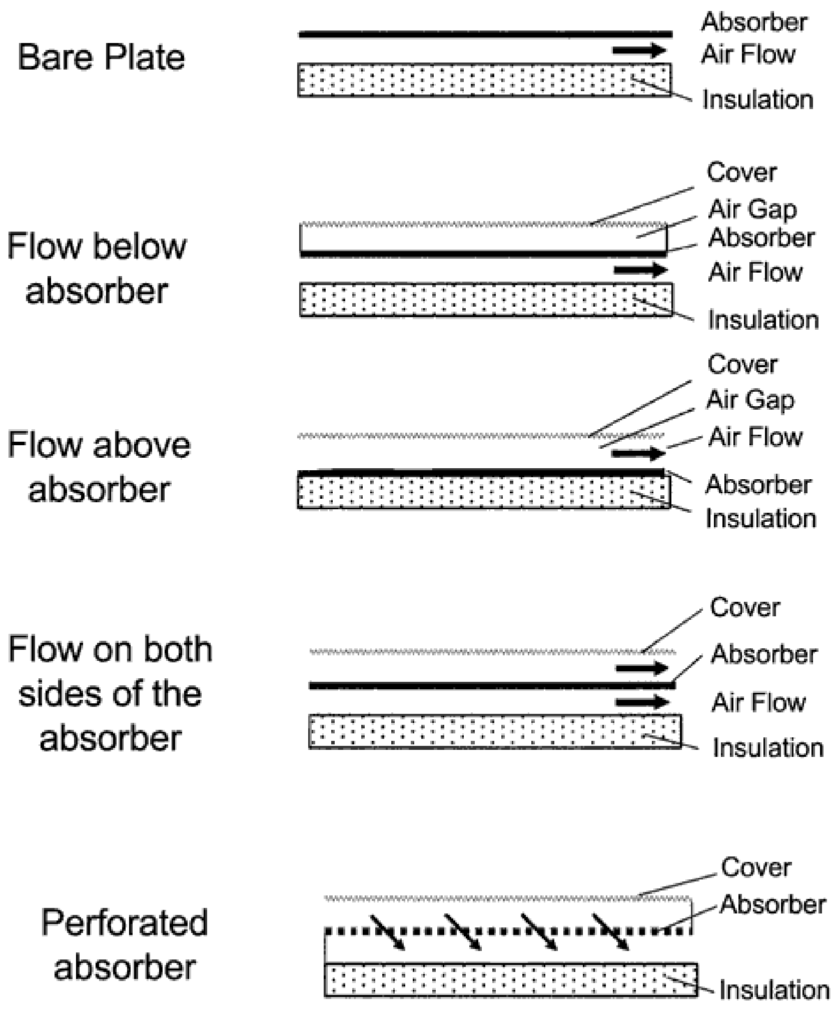


Fig. 67: Air flow principles in solar air collectors [57]

The simplest type of collector is the bare plate which consists simply of the air chamber between the insulation and the uppermost surface of which acts as the absorber plate. The covered plate collector in its many forms utilises a translucent cover above the absorber plate. Compared with the bare plate collector higher collection efficiencies are obtainable with covered plate collectors but at the expense of increased complexity and cost.

A major advantage of the bare plate collector is that it can be easily incorporated into the roof of a dryer or storage building. Corrugated iron is a popular and inexpensive roofing material in many areas and when painted black forms an excellent solar absorber. A false ceiling can be fixed to the roof joists so forming a shallow duct running the length of the building and easily connected to a fan via ducting at one end of the building. The heat available from the collector is weather dependent and consideration should therefore be given as to whether solar energy should be the sole source for heating the air or a supplement to more conventional heating systems.

A major drawback of the conventional flat plate air collector is the low heat transfer coefficient between the flat plate absorber and the flowing air stream. The heat transfer can be improved by adding fins, or by making the absorber plate vee corrugated, or by roughing the surface of the absorber at the rear. In Fig. 67 one can see more possible absorber profiles for air collectors.

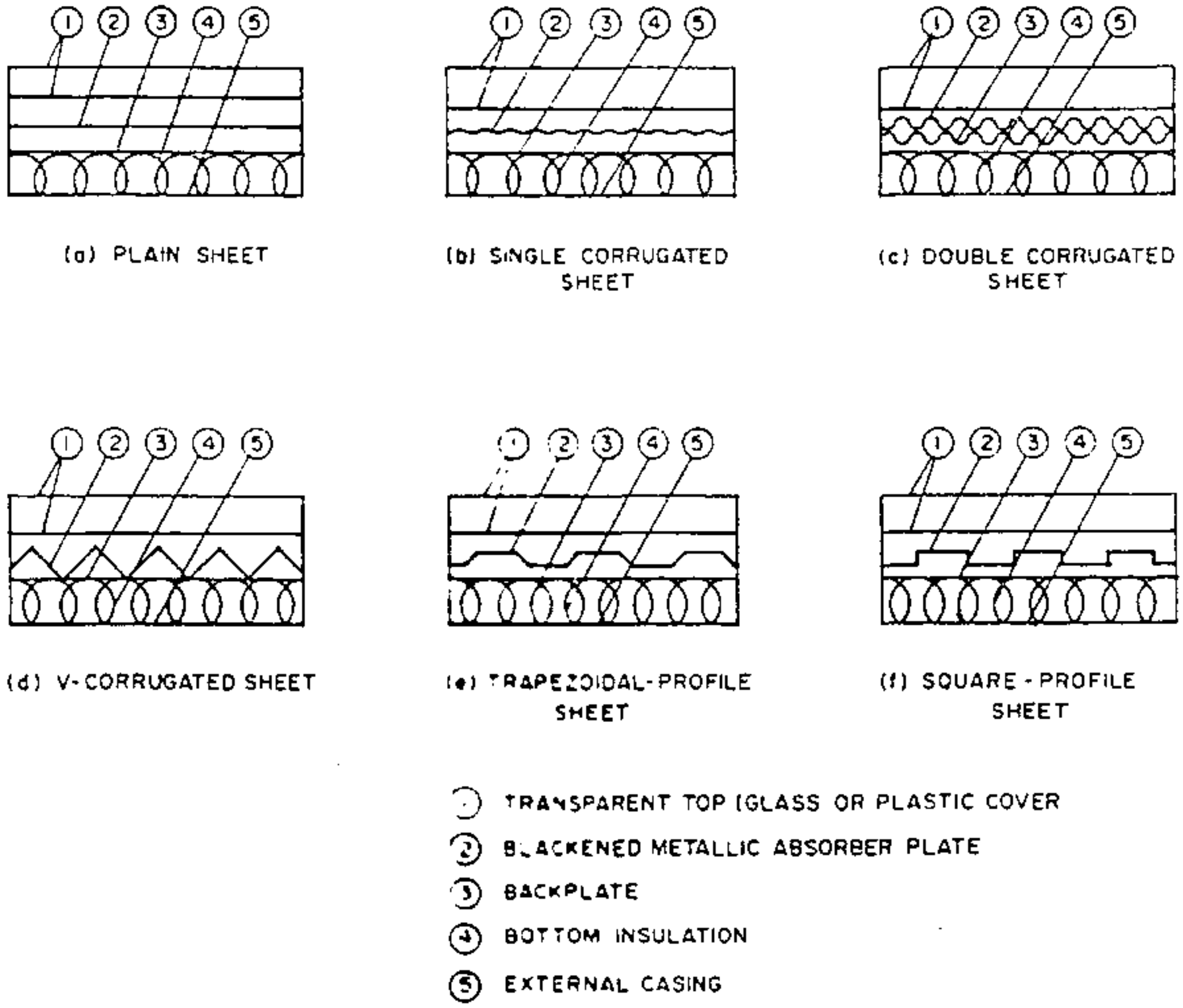


Fig. 68: Possible absorber profiles for collectors with flow on both sides [12]

Domestic Solar Heating Pvt. Ltd., Harare and AEE-INTEC, AUSTRIA developed a simple and inexpensive design of a flow-on-both-sides absorber. It consists of tow plies of corrugated copper sheets, a wooden frame and a cover of glass. The copper sheets are profiled in a very simple tool made by local craftsman, Fig. 68. Two of those plates are positioned on top of each other in the frame. In between the air channels are formed. The upper side of the plates are coated with black paint and in the wooden frame is a glass cover mounted.

Fig. 69: Tool to corrugate the copper sheets

Fig. 70: Prototype of the air collector prior to the coating with black paint and without glass cover

Fig. 71: Coated air collector before mounting the glass cover.

Fig. 72: Measuring the air temperature inside the collector.

7.1.3 Performance

The performance of a flat plate collector can be quantified by calculation of the collection efficiency; the ratio of the heat gathered by the collector to the insolation incident on its surface. The collection efficiency is a function of the air velocity through the collector, the geometry of the air duct, the absortivity of the absorption surface, and the transmissivity of the cover(s). [57]

The ratio between solar irradiation on a certain surface and thermal power in the outlet air:

$$\eta = \frac{\dot{Q}_u}{A_c G}$$

$$\dot{Q}_u = \dot{m} \cdot c_p (T_o - T_i)$$

T_i collector inlet temperature, °C
T_o collector outlet temperature, °C
G solar global irradiance, W/m²
Q heat energy, J
 mass flow rate, kg/s
c_p specific heat of air, kJ/kgK
Q_u useful gain of the collector, W
A_c collector reference area, m²

Usually it is helpful to present the performance in two different diagrams:

- Efficiency versus temperature difference between outlet temperature and ambient divided by irradiation $(T_o-T_a)/G$
- Efficiency versus mass flow rate for $T_i = T_a$

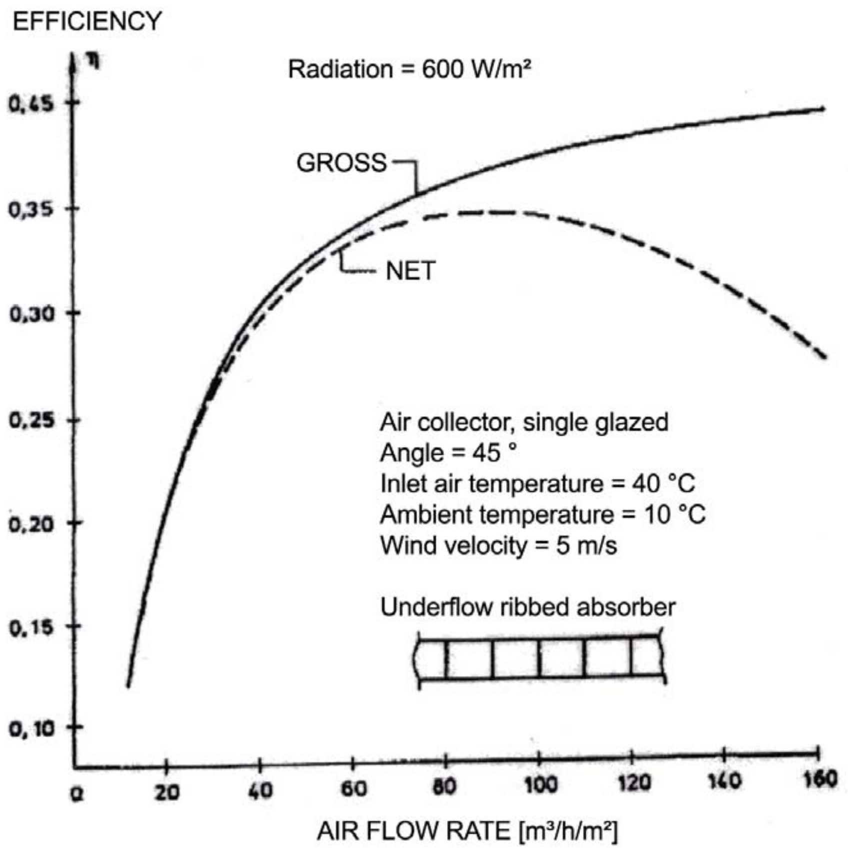


Fig. 73: Gross and net efficiency of an typical air collector. [57]

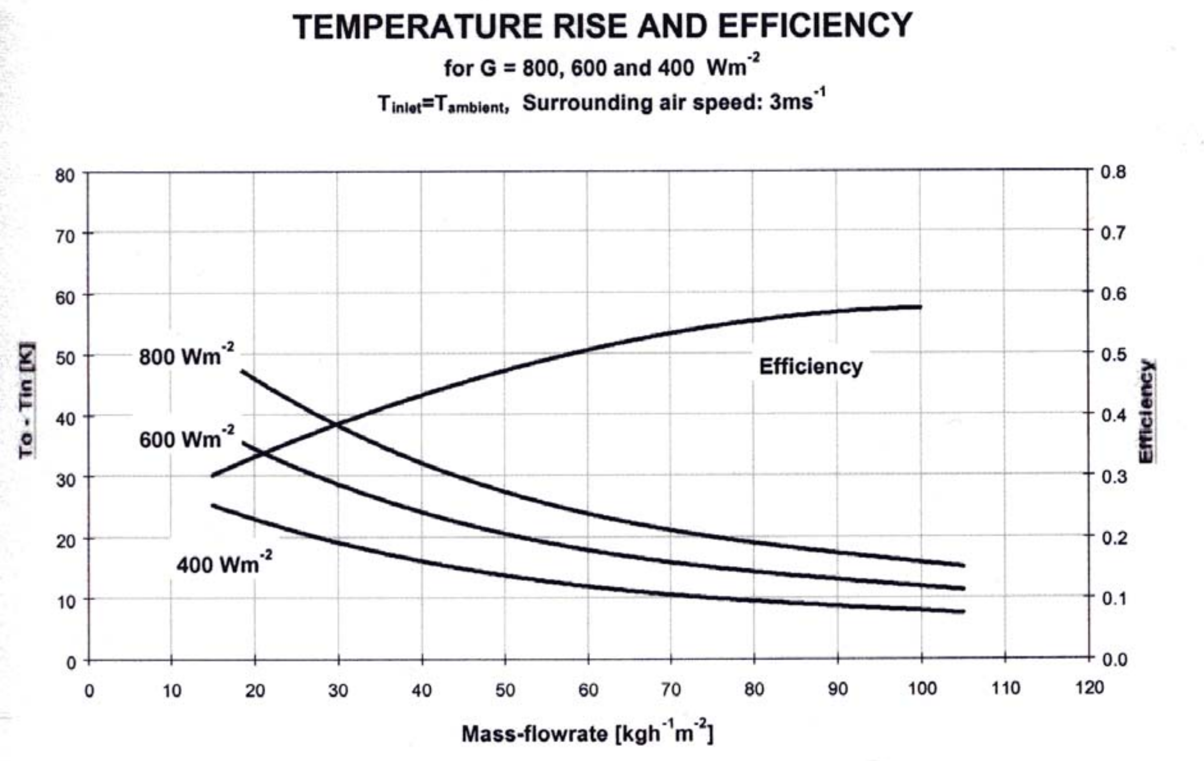


Fig. 74: Temperature rise and efficiency. [57]

7.1.4 Optimizing collector operation

Great importance lies in finding a compromise between high heat transfer (which is mainly dependent on highly corrugated or perforated absorbers) and the pressure drop, (such constructions mostly cause high pressure drop) which increases the electric need for the fan. But depending on the air system, the pressure drop caused by the succeeding ducts, hypocausts, dampers, etc … must be taken into consideration as well as choosing high mass flow rates to run the collector with high efficiency.

Apart from the effect of the characteristics of the collector itself, the output of the solar system is strongly dependent on the inclination angle of the collector to the sun.

Table 13*: Tilt angle for different latitudes and seasons*

Latitude [degree]	**Best collector tilt in:**					
	June	Orientation	**Sept./March**	Orientation	**December**	Orientation
50 N	26.5	S	50	S	73.5	S
40 N	16.5	S	40	S	63.5	S
30 N	6.5	S	30	S	53.5	S
20 N	3.5	N	20	S	43.5	S
15 N	8.5	N	15	S	38.5	S
10 N	13.5	N	10	S	33.5	S
Equator = 0	**23.5**	**N**	**0**	**-**	**23.5**	**S**
10 S	33.5	N	10	N	13.5	S
15 S	38.5	N	15	N	8.5	S
20 S	43.5	N	20	N	3.5	S
30 S	53.5	N	30	N	6.5	N
40 S	63.5	N	40	N	16.5	N
50 S	73.5	N	50	N	26.5	N

The largest yield is obtained when the collector is always orientated perpendicular to the sun. However, the optimal tilt angle for the collectors varies according to the season, as the sun is higher in the sky in summer than in winter. As a general rule, *the optimum angle of tilt is equal to the degree of latitude of the site* . But the minimum angle of the collector should be 15 degree to assist the thermosiphon effect**.** The following table shows optimum tilt angles of different latitudes and seasons.

7.1.5 Pressure drop

In general, the pressure drop should be low to keep the necessary electrical power for the fan as low as possible.

Pressure drop is about square function of air velocity. It increases about linear with air density. Air density is also depending on the location, since it is depending on the atmospheric pressure.
It depends further on size of the air gap and on the length of the collector. In choosing a fan, the total pressure drop of the collector and the dryer has to be calculated.

Example: Calculation of pressure drop in a flat plate collector

[58] The air velocity is calculated from the given air flow rate $\dot{V}$ and the cross-sectional area A of the collector by:

$$c = \frac{\dot{V}}{A}$$

Reynolds is calculated with:

$$Re = \frac{c \cdot d}{\nu}$$

Usually a collector has no circular ducts, so the hydraulic diameter d_H for rectangular ducts should be used to calculate Re:

$$d_H = \frac{4A}{U}$$

The friction factor is calculated from the following relationships:

Re < 4,000 → λ = 64/Re (for smooth and rough surfaces and circular cross area)

4,000 < Re < 20,000 → $\lambda = 0.3164\ Re^{-0.25}$ (Blasius – Law)

The dynamic head loss coefficient ζ is tabulated [56, 58] for various expansions and contractions geometries. The pressure drop across the collector is given by:

$$\Delta p = \left(\lambda \frac{l}{d} + \sum \zeta \right) \frac{\rho \cdot c^2}{2}$$

λ	[1]	friction factor
l	[m]	length of the collector
d	[m]	diameter of the collector

c [m/s] air velocity
ζ [1] dynamic head loss coefficient
ρ [kg/m³] air density
ν [m²/s] viscosity
$\dot{V}$ [m³/h] air flow rate
A [m²] cross sectional area
d_H [m] hydraulic diameter
U [m] perimeter

7.1.6 Durability

All materials should be resistant to heat, dampness and light. In particular, synthetics should be resistant to ultraviolet light and high temperatures. The collector should be air- and watertight. Absorber surfaces have to be resistant to both heat and moisture.

7.2 Ventilation

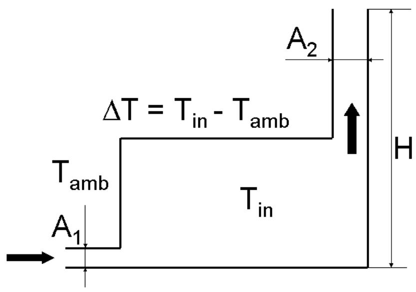
The air flow rate is crucial to the overall system performance. Too high an air flow consumes excessive fan power and too low rates cause poor thermal performance of the system. In summary:

- The higher the mass-flow rates, the higher the efficiency of the collector.
- The electrical energy for the fan increases with the mass flow rate.
- The effect of leakages increases with the air flow rate.
- For drying purposes a certain temperature level is often needed.

7.2.1 Natural ventilation

[56] The natural ventilation due to the chimney effect is described by the following equation:

$$c_2 = \sqrt{\frac{gH\frac{T_{in} - T_{amb}}{T_{in}}}{1 + \frac{A_2^2}{A_1^2}}}$$



c_2 [m/s] air velocity in the upper opening
H [m] height
T_{in} [°C] internal temperature difference
T_{amb} [°C] ambient temperature
A_1 [m²] area of the lower opening
A_2 [m²] area of the upper opening

7.2.2 Electrical fans

Fans are flow machines designed to convey a certain air volume and to increase the pressure in order to overcome the resistance of the system. They should work with the best possible efficiency and at lowest possible noise level.

Fans can be divided and classified according to the air flow direction through the fan. The major types are axial flow, radial flow and mixed flow.

Axial fan
The air enters and leaves the fan axially. The main modules of an axial ventilator are the hub with the blades, the casing and the drive. There are several components designed to increase the efficiency of an axial blower, such as an inlet nozzle, stator, diffuser and moveable blades. The air flow of an axial fan can be controlled by:

- ✓ dampers on the extraction or pressure side of the fan;
- ✓ variation of the blade angle;
- ✓ variation of the rotational speed.

If energy savings are considered, the best way to change the air flow rate of a fan is to vary the speed of rotation. A common position for the drive is the hub of the fan.

The motor is cooled by the air flow and all the heat form the motor can be used, while the open cross section is reduced. Typical operating conditions of standard axial fans are high volume rates and low delivery pressure, e.g. ventilation of a sunspace or exhaust-air extraction from rooms.

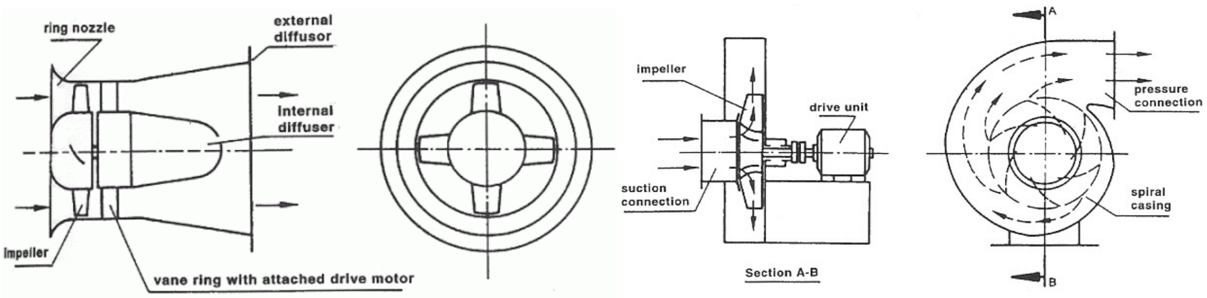


Fig. 1: Axial fan (left) and radial fan (right) [59]

Radial fan
The air enters axially and leaves radially. These fans have usually a spiral casing with single or double inlet. Some special casings allow the use of a radial fan in a round duct. There are different shapes of blades, which can be forward-curved, radial or back-ward-curved. It is possible to have the motor external to withstand high flow temperatures and to avoid heat gains due to the motor. A radial fan typically achieves a lower volume rate and a higher pressure increase than an axial fan. Radial fans are typically used in ducts with a higher flow resistance, e.g. ducts with air heating, cooling and filter devices.

Cross-flow fan
The air flow runs through the impeller transversally. The volume increases proportionally to the impeller width. Cross-flow fans are suitable for blowing into narrow ducts or grooves with a broad width but with typically low volume rate and efficiency. An advantage of cross-flow fans is their low noise emission, on account of which they are used in applications where the fan is placed near the user, e.g. an underfloor convector.

By the use of DC motors in combination with a photovoltaic panel, it is necessary to take into account that the start-up power can be up to five times higher than the maximum power during operation.

The efficiency is an important factor in the selection of a fan. It is defined as the coefficient:

$$\frac{dpV}{P} = (p_{supply} - p_{inlet}) \cdot \frac{flowrate}{power_{motor}}$$

The efficiency of a common axial fan lies between 30 and 70 %.

7.2.3 Dimensioning an electrical fan

The motor output of the fan can be calculated as follows:

$$P_M = \frac{\dot{V} \cdot \Delta p_T}{\eta_L \cdot \eta_M}$$

P_M	[W]	power of the motor
Δp_T	[Pa]	total pressure increase
η_L		fan efficiency factor
η_M		motor efficiency factor

The total pressure increase Δp_T consists of the static pressure difference Δp_S and the dynamic pressure p_d occurring at the outlet of the fan. The static pressure difference is the pressure loss in the system (pipe friction, formed parts, trays).
The efficiency is dependent on the type and size of the fans as well as on the working point. Attention must be paid to the fact that radial fans with backward-curved or forward-curved blades have the highest power consumption when they are blowing free.

7.2.4 Fan control

The air flow or the required pressure increase is adjusted to the respective requirements by way of different control mechanisms, such as:

- ✓ On/off control
- ✓ Change of rotational speed with electronic controllers or with coupled to insulation on PV
- ✓ Throttling with a damper or throttling flap
- ✓ Bypass control
- ✓

7.2.5 Power supply from solar cells

Photovoltaic (PV) cells offer an ideal energy supply for fans. The electricity produced by the solar cells is not only supplied at the same time but also increases automatically with an increasing demand. As solar cells produce DC, the choice of DC motors is obvious. For solar air systems, PV modules with a voltage of 12 V, a power of 50 W_p and a size of 0,5 m² have proved to be suitable; this corresponds to a maximum power at an insulation of 1000 W/m² and a solar cell temperature of 25 °C.

The dependency of the performance of the PV-drive on the solar radiation shows certain advantages over grid-driven fans. The fans of the solar tunnel dryer are directly coupled to the solar panel, which results in a simple and therefore very reliable system. However, the downside of this system is that it also produces a fluctuating air flow rate – the air flow rate is high under sunny conditions and low when clouds appear. By using a well adapted direct coupled system, the maximum temperature within the drying chamber can be automatically controlled and adjusted to a certain level by the number of fans installed. The maximum permissible drying temperature will be exceeded only for a short time period, which is a prerequisite to ensure that the product quality does not deteriorate. Moreover, due to the higher temperature level inside the drying chamber the drying process will be accelerated, resulting in a shorter drying time.

The adaptation of the characteristic curves of the blade and motor of the fan, as well as the solar panel, is of great importance for the performance of the drive. In particular, it is essential to ensure that the fan starts to operate even at low levels of radiation. This is necessary to remove the moisture from the drying compartment so as to prevent spoilage and or growth of mould and yeast. Cooling fans of cars, which have been used instead of the original ones in several attempts due to their ease of availability and low cost, do not meet this requirement and should therefore not be used.

Table 14: Exemplary technical data of the drive systems (freely blowing) [60]

Drive system	**Mains-powered**	**Photovoltaic (PV)**	
Components	Radial fan	Axial fan	Solar module
Maker	ebm	Fiat	Solarex
Type	R4E 280-AD0805	Uno, gasoline-fueled model	MSX 83
Rated voltage [V]	220	12	16.9
Rated current [A]	0.33	7.0	4.92
Nominal consumption [W]	70	84.0	83.2
Air flow rate [m³/h]	1360	1520	
Rated speed [RPM]	1400	2800	

8 References

[1] BUX, M.e.a.: Solar crop drying in developing countries, Berne, (2002).
[2] FULLER, R.J.: Solar Drying of horticultural produce: Present practice and future prospects, Postharvest News and Information 4 (3), pp (1993).
[3] ITDG: Drying of Foods, http://itdg.org, Technical Brief
[4] PRYOR, T.: Solar Drying, (2001).
[5] ARFAOUI, Y.: Improving the welfare and increasing the income generation by the commercialisation of sustainable energy echnology - commercialisation of solar dryer for agricultural products., Copenhagen, (n.y.).
[6] EKECHUKWU, O.V.a.N.B.: Review of solar-energy drying systems II: an overview of solar drying technology, Energy Conversion & Management 40 pp 615-655, Pergamon (1999).
[7] BUX, M., MÜHLBAUER, W., BAUER, K., KÖHLER, B.: Solar crop drying in developing countries, Berne, (2002).
[8] ITDG: Solar Drying, http://itdg.org, Technical Brief
[9] EKECHUKWU, O.V.: Experimental studies of integral-type natural-circulation solar-energy tropical crop dryers, Ph.D. (1987).
[10] FABRE, M., MIHAILOV, S.: Expert consultations on planning the development of sun drying techniques in Africa, Food and Agriculture Organization of the United Nations, http://www.fao.org/inpho/vlibrary/x0018e/X0018E.htm, (1985).
[11] SPEIRS, C.I., COOTE, H.C.: Solar Drying: Practical Methods of Food Preservation, (1986).
[12] DAUTHY, M.E.: Fruit and vegetable processing, Rome, (1995).
[13] AYENSU, A.: Dehydration of food crops using a solar dryer with convective heat flow, Solar Energy 59 pp (1997).
[14] GOYAL, R.K., TIWARI, G.N.: Performance of a reverse flat plate absorber cabinet dryer: a new concept, Energy Conversion & Management 40 pp 385-392, Pergamon (1999).
[15] BENA, B., FULLER, R.J.: Natural convection Solar Dryer with biomass back-up heater, Solar Energy 72 (1), pp (2002).
[16] BASSEY, M.W.e.a.: Problems and solutions for natural convection solar crop drying, Senegal, (1987).
[17] Brace-Research-Institute: Types of solar agricultural dryers, Sunworld 4 (6), pp 181, (1980).
[18] BRENNDORFER, B., KENNEDY, L., BATEMAN, C.O.O., MREMA, G.C., WEREKO-BROBBY, C.: Solar dryers- their role in post harvest processing., London, (1985).
[19] HISLOP, D.: Energy Options – Chapter 3: Heat from Solar Energy., (1992).
[20] GRUPP, M., BERGLER, H., OWEN-JONES, M., SCHRÖDER, G.: Comparative Test of Solar Dryers, Almeria, (1995).
[21] ESPER, A., MÜHLBAUER, W.: Solar tunnel dryer for fruits., Plant research and development 44 pp (1996).
[22] HENSEL, O., ESPER, A.: The Hohenheim Solar Tunnel Dryer - 20 years of success, ITDG Food Chain, http://www.innotech-ing.de/, (2003).
[23] GREEN, M.G., SCHWARZ, D.: Solar Drying Equipment: Notes on three dryers, gtz-gate, (2001).
[24] KAMARUDDIN, A.e.a.: Recent development of GEHE Solar Drying in Indonesia, Drying Technology 19 (2), pp Marce Dekker (2001).
[25] JENSEN, S.O.: Inspection of solar dryer in Ghana, (2001).
[26] PROCTOR, D.L.: Grain Storage Techniques, Rome, (1994).
[27] GREEN, M.G., SCHWARZ, D.: Solar Drying Technology for Food Preservation, gtz-gate, (2001).
[28] MULOKOZI, G.e.a.: Improved Solar Drying of Vitamin A-rich Foods by Women´s Groups in the Singida District of Tanzania, Washington, Research Report Series (2000).

[29] COSTA, A.R.S., et.al.: Natural drying process for tropical fruits,
[30] RERIC: Renewable energy technologies in Asia, A Regional Research and Dissemination Programme, Phase II,, Thailand, (2002).
[31] Anonym: A solar-biomass hybrid dryer for pineapple farmers in the Philippines, Asian Institute of Technology, http://www.retsasia.ait.ac.th/drysotry.htm, (1993).
[32] CONDORí, M., ECHAZÚ, R., SARAVIA, L.: Solar drying of sweet pepper and garlic using the tunnel greenhouse dryer, Renewable Energy 22 pp 447-460, Pergamon (2001).
[33] OSAKWE, A., WEINGARTMANN, H.: Solare Konservierung von Obst und Gemüse, erneuerbare energie 3-98 pp 31-35, AEE-INTEC (1998).
[34] OSAKWE, A.: Solartrocknung von Obst und Gemüse in Ouagadougou, Burkina Faso, Vienna, (1995).
[35] VARADHARAJU, N.e.a.: Coffee cherry drying: a two-layer model, Drying Technology 19 (3 & 4), pp Marcel Dekker (2001).
[36] IEA-SHC: Solar Crop Drying, (1996).
[37] Anonym: Solar coffee dryer field test in Miramar, Costa Rica: Lessons Learned to be applied in the small grower - small roaster direct connection program, Massachusetts, (1996).
[38] ADAIR, D.: Coffee drying in Kenya, Rome, (1985).
[39] EXELL, R.H.B.: Basic Design Theory for a Simple Solar Rice Dryer, Renewable Energy Review Journal 1 (2), pp 1-14, (1980).
[40] MUMBA, J.: Develpment of a photovoltaic powered forced circulation grain dryer for use in the tropics, Renewable Energy 6 (7), pp 855-862, Elsevier (1995).
[41] BALOCH, U.K.: Post-harvest operations: Chapter VI Wheat, (n.d.).
[42] LANTIN, R.: Post-harvest Operations: Chapter X Rice, (n.d.).
[43] PROCTOR, D.L.: Grain Storage Techniques, Rome, (1994).
[44] ISLAS-RUBIO, A.R., HIGUERA-CIAPARA, I.: Post-harvest compendium: Chapter XIX Soybean, (n.d.).
[45] TETER, N.: Paddy Drying Manual, Rome, (1987).
[46] BROOKER, D.B., BAKKER-ARKEMA, F.W., HALL, C.W.: Drying cereals grains, Westport: Avi Publishing Co. Inc. pp 265, (1974).
[47] BROOK, R.C., FOSTER, G.H.: Drying, cleaning and conditioning, (1981).
[48] SIMATE, I.N.: Simulation of the mixed-mode natural-convection solar drying of maize, Drying Technology 19 (6), pp 1137-1155, Marcel Dekker, Inc. (2001).
[49] BALA, B.K., MONDOL, M.R.A.: Experimental Investigation of Solar Drying of fish using solar tunnel dryer, Drying Technology 19 (2), pp (2001).
[50] BASUNIA, M.A., ABE, T.: Thin-layer solar drying characteristics of rough rice under natural convection, Journal of Food Engineering 47 pp 295-301, Elsevier (2000).
[51] BUX, M., MÜHLBAUER, W., BAUER, K., KÖHLER, B.: Solar Assisted Drying of Timer in Industrial Scale, Southern African Forestry Journal pp (2001).
[52] ARMSTRONG, J.P., HALL, C.S.: Wood industry fact sheet, (n.d).
[53] YANG, K.C.: Solar Kiln performance at high latitude, 48° N, Forest Products 30 (3), pp (1980).
[54] WENGERT, E.M.: Solar heated lumber dryer for the small business: Utilization and Marketing, Blacksburg, (1980).
[55] BOIS, P.J.: Constructing and operating a small solar-heater lumber dryer, Forest Products Utilization Technical Report No. 7 (Re-Issue 3/89), pp (1989).
[56] IEA-SHC: Solar Air Systems, (1998).
[57] FECHNER, H.: IEA Task 19 Solar Air Systems, Investigations on Series Produced Solar Air Collectors, Summary report, Vienna, (2000).
[58] HAAGE, H.: Maschinenkunde: Kraft- u. Arbeitsmaschinen, Wien, (1992).
[59] HASTINGS, S.R., MORCK, O.: Solar air systems: a design handbook, London, (2000).
[60] HÄUSER, M., ANKILA, O.: Solar Drying in Morocco,
[61] SARWAR, G., WILLIAMS E.A., ROBINSON, A.P.: Survey of commercially available Wood and Agricultural Residue Combustion Systems, (Engineering Series No. 1), pp 21, Chatham: Natural Resources Institute (1992).

[62] MAHIN, D.B.: Industrial Energy and Electric Power from Wood Residues, Arlington, (1991).
[63] ROBINSON, A.P.: The Design and Development of a Suspension Burner System for Particulate Forestry and Agricultural Residues, Chatham, (1991).
[64] BREAG, G.R., CHITTENDEN, A.E.: Producer Gas: its Potential and Application in Developing Countries, London, (1979).
[65] HOLLINGDALE, A.C.: Survey of Manufacturers of Gasifier Power Plant Systems, London, (1983).
[66] ERIKSSON S., P.M.: The Briquetting of Agricultural Wastes for Fuel, Rome, (1990).

Appendix

Crop Data

The crop data are an extract of the study « Potential for Solar Drying in the World », prepared by Enermodal Engineering Ltd., Canada and ECOFYS Energy & Environment, Netherlands [12].

Apples

Initial Moisture Content:	80-85 %	
Final Moisture Content:	20-24 %	
Energy Required (MJ/kg):	1.502	
Maximum Temperature:	70 °C	
Storage	Leather is wrapped in polypropylene	
Drying Methods	**Low Temperature**	**High Temperature**
	1. Tunnel 2. forced air dehydrator for leather	3. dry sulphuring 4. wet sulphuring
Required drying time	1. 5-6 hours 2. 3.5 hours	3. 30-40 min 4. 10 min
Required drying temperature	1. 75-55 °C 2. 45 °C	

Apricots

Initial Moisture Content:	85 %	
Final Moisture Content:	15-25 %	
Energy Required (MJ/kg):	1.666	
Maximum Temperature:	65 °C	
Storage	Leather is wrapped in polypropylene	
Drying Methods	**Low Temperature**	**High Temperature**
	1. Tunnel 2. forced air dehydrator for leather 3. sulphuring 4. sun drying	
Required drying time	1. 10-15 hours 2. 3.5 hours 3. limited through-put time 4. 4,5 days	
Required drying temperature	1. 70-60 °C 2. 45 °C	°C

In apricots, the decomposition of chlorophyll causes a positive effect on the colour. Therefore direct exposition to solar radiation is recommended.[1]

Bananas

Initial Moisture Content:	70-80 %	
Final Moisture Content:	7-15 % 2 % (powder) 8 % (flour)	
Energy Required (MJ/kg):	1.679	
Maximum Temperature:	70 °C	
Storage	Stored in bundles, hung on racks in warehouse. Wrapped in leaves and bound tightly, vacuum sealed, dry conditions; may be treated with sulphating or by fumigation with methyl bromide (dried products) or an antioxidant (chips) Fruit bars are wrapped in cellophane	
Drying Methods	**Low Temperature**	**High Temperature**
	1. Sun-drying 2. oven-drying 3. batch or in-bin drying after osmotic dehydration for candied fruit 4. warehouse drying 5. spray or drum-drying (powder)	6. Tunnel or cabinet 7. osmotically (2000 ppm SO_2) usually followed by sun drying or air drying 8. sun and mechanical 9. forced air dehydrator for leather
Required drying time	1. several days (4-6) 2. several hours or days 3. several hours 4. several hours 5. 7-8 hours (flour)	6. 7. 2 hours followed by a day of solar 8. 10 hours solar plus 16 hours electric or steam power (fruit bars) 9. 3.5 hours
Required drying temperature	30-70 °C 60 °C (tunnel for powder) 75 °C inlet temperature and 45 °C outlet temp. (flour)	70 °C 45 °C

Barley

Initial Moisture Content:	15-20 %	
Final Moisture Content:	13-14 %	
Energy Required (MJ/kg):	0.055-0.168	
Maximum Temperature:	43 °C for mc > 24 % 49 °C for mc < 24 % 60 °C for grains to be milled if mc > 25 % 66 °C for grains to be milled if mc < 25 % 120 °C for grain for feed 55 °C for barley destined for brewery	
Storage	In silos without aeration and circulation In silos with sufficient aeration In ventilated storage bags	
Drying Methods	**Low Temperature**	**High Temperature**
	De-central in storage driers (silos, floor)	De-central batch dryers at farms or central large-scale continuous process at drying facility
Required drying time	Days-weeks; drying during storage	Minutes; drying and storage separately
Required drying temperature	Δ 3-5 °C	50 – 250 °C

Cassava, Mainoc, Yuca (*Manihot esculenta*)

Initial Moisture Content:	62 – 75%	
Final Moisture Content:	14-17 %	
Energy Required (MJ/kg):	1.105	
Maximum Temperature:	150 °C	
Storage	In-ground, in water as roots; in silos as chips; sealed polyethylene bags as gari	
Drying Methods	**Low Temperature**	**High Temperature**
	1. Chips dried in sun 2. Chips in cabinet solar dryer 3. Tunnel Dryers 4. Flour and tapioca from Drums	5. oven dried 6. pneumatic dryers
Required drying time	1. several days-weeks 2. several days (92 h) 3. several hours 4. several hours	5. several hours 6. several hours
Required drying temperature	30-60 °C	
Drying Constant	Kc = 0.031, ke=0.012 for Chips	

Cassava leaves[2]

Initial Moisture Content:	80 %	
Final Moisture Content:	14 %	
Energy Required (MJ/kg):	1.586	
Maximum Temperature:		
Storage	Small huts or by cooking pit or oven	
Drying Methods	**Low Temperature**	**High Temperature**
	1. Sun drying 2. Leaves in cabinet solar dryer 3. incidental drying above cooking pit or oven	
Required drying time	1. several days 2. two days (46 h) 3. sometimes weeks	
Required drying temperature	30-60 °C	
Drying Constant	kc=0.047, ke=0.012	

Chillies and Peppers

Initial Moisture Content:	75-80 %	
Final Moisture Content:	5-14 %	
Energy Required (MJ/kg):	1.610	
Maximum Temperature:	90 °C	
Storage	Bags and bulk storage in warehouse	
Drying Methods	**Low Temperature**	**High Temperature**
	Sun drying	Kiln drying
Required drying time	Several days (6-8)	Several hours
Required drying temperature	40 °C	90 °C

Cocoa Beans

Initial Moisture Content:	60-80 %; 50-55 %	
Final Moisture Content:	25-30 %; 6-7 %	
Energy Required (MJ/kg):		
Maximum Temperature:		
Storage		
Drying Methods	**Low Temperature**	**High Temperature**
	1. sun drying 2. batch or in-bin drying with wood or crop waste, coal or diesel fuel burned dryers 3. solar dryers drying during storage (45-50 °C)	Central large-scale continue process at drying facility; drying and storage separately
Required drying time	1. Several days (4-9) 2. several hours (32-42 h) 3. several hours (48 h)	Minutes
Required drying temperature	30-60 °C	

Continuous air flow required during the first phase of solar drying.[1]
There are numerous types of dryers but an essential feature of all must be that any smoky products of combustion do not come in contact with the beans otherwise taints will appear in the final product. [2]

[2] AYENSU, A.: Dehydration of food crops using a solar dryer with convective heat flow, Solar Energy Vol. 59, Nos. 4-6, pp 121-126, Elsevier Science (1997).

Coffee

Initial Moisture Content:	45-65 %	
Final Moisture Content:	9-12 %	
Energy Required (MJ/kg):	0.855- 0.865	
Maximum Temperature:		
Storage	Bags and bulk storage in warehouses and silos	
Drying Methods	**Low Temperature**	**High Temperature**
	1. sun drying 2. batch or in-bin drying with wood or crop waste burned for heat 3. solar drying	Roasting
Required drying time	1. Several days (3-7) 2. several hours 3. several hours (40-58)	
Required drying temperature	30-60 °C	

For Arabica coffee, a period of exposure to sunlight is considered inviolable for the development of full flavour in the roasted bean.[3-5]

Grapes

Initial Moisture Content:	75- 80 %	
Final Moisture Content:	15-20 %	
Energy Required (MJ/kg):	1.444	
Maximum Temperature:	70 °C	
Storage	Leather is wrapped in polypropylene	
Drying Methods	**Low Temperature**	**High Temperature**
	1. sun drying 2. Forced air dehydrator for leather	
Required drying time	1. 8-10 days 2. 3.5 hours	
Required drying temperature	45 °C	

Continuous air flow required during the first phase of solar drying.[1]
In grapes, the decomposition of chlorophyll causes a positive effect on the colour. Therefore direct exposition to solar radiation is recommended.[1]

Mushrooms

Initial Moisture Content:	%	
Final Moisture Content:	%	
Energy Required (MJ/kg):		
Maximum Temperature:		
Storage	Opaque, air-tight containers (drums or packages), sometimes with a desiccants	
Drying Methods	**Low Temperature**	**High Temperature**
Required drying time		
Required drying temperature	°C	°C

Maize

Initial Moisture Content:	20-35 %	
Final Moisture Content:	8-15 %	
Energy Required (MJ/kg):	0.254 – 0.565	
Maximum Temperature:	60 °C 43 °C (then seeds lose their viability) 43 °C for mc > 24 % 49 °C for mc < 24 % 60 °C for grains to be milled if mc > 25 % 66 °C for grains to be milled if mc < 25 % 120 °C for grain for feed	
Storage	- at households stored in various ways from in the cob to sealed containers - on larger farms in special constructions (in bags or in bulk) - central large-scale farmers and traders store amize (12-13 %) in bags or bulk in warehouses or silos	
Drying Methods	**Low Temperature**	**High Temperature**
	- sun and field and banda(wood fire in storage (Africa) followed by incidental (Gulf of Guinea), tap (elevated storage)(Cameroon), bliva (elevated pile of cobs), maize crib (tap-type but better made)(Nigeria), IRRI hot air dryer - shallow batch dryer (2.4-6 m³/min/m²)	
Required drying time	Several weeks	Several hours
Required drying temperature	On average less then 35 °C	

Mangoes

Initial Moisture Content:	80-85 %	
Final Moisture Content:	12-18 %	
Energy Required (MJ/kg):	1.564	
Maximum Temperature:	70 °C	
Storage	Oval bundles and hung Larger amounts stored in millet granaries Fruit bars are wrapped in cellophane Leather is wrapped in polypropylene	
Drying Methods	**Low Temperature**	**High Temperature**
	1. sun or solar (decentral small-scale batch system at farm) 2. tunnel 3. vacuum-drying 4. forced air dehydrator for leather	5. osmotically (8000 ppm SO_2) 6. sun and mechanical (fruit bars)
Required drying time	1. 1-2 weeks 2. – 3. – 4. 2 hours	5. – 6. 10 hours solar plus 16 hours electric or steam power
Required drying temperature	1. 70 °C; 55 °C in last stage of drying	6. 55 °C at beginning to a high of 70°C

Papayas

Initial Moisture Content:	%	
Final Moisture Content:	%	
Energy Required (MJ/kg):		
Maximum Temperature:		
Storage	Leather is wrapped in polypropylene	
Drying Methods	**Low Temperature**	**High Temperature**
	Forced air dehydrator for leather	Osmotically (2000 ppm SO_2)
Required drying time	3.5 hours	4 hours
Required drying temperature	45 °C	70 °C

Pine apples
Turn black above 47 °C

Potatoes

Initial Moisture Content:	70-75 %	
Final Moisture Content:	8-13 % < 4 % for powder	
Energy Required (MJ/kg):	1,453	
Maximum Temperature:	75-85 °C	
Storage	Warehouse/silo	
Drying Methods	**Low Temperature**	**High Temperature**
	Sun (for chips) Plates heated with hot water, under vacuum	Drum (for powder) Spraying in hot air (powder)
Required drying time	Sometimes several days	< 1 hour 1/50 s
Required drying temperature	30 – 60 °C 50-70 °C	75-85 °C 130-150 °C

Rice

Initial Moisture Content:	20-30 %	
Final Moisture Content:	12-18 %	
Energy Required (MJ/kg):	0.218 – 0.351	
Maximum Temperature:	50 °C 43 °C for mc > 24 % 49 °C for mc < 24 % 60 °C for grains to be milled if mc > 25 % 66 °C for grains to be milled if mc < 25 % 120 °C for grain for feed	
Storage	In silos without aeration and circulation In silos with sufficient aeration In ventilated storage bags	
Drying Methods	**Low Temperature**	**High Temperature**
	De-central batch drying system at farms (silos, floor)	Central large-scale continuous-flow driers and storage driers
Required drying time	Days-weeks; drying during storage	Minutes; drying and storage separately
Required drying temperature	< 50 °C	

Sugar cane

Initial Moisture Content:	75 %	
Final Moisture Content:	%	
Energy Required (MJ/kg):		
Maximum Temperature:		
Storage	Raw sugar stored in piles in warehouses before shipping to a refinery	
Drying Methods	Following other treatments, sugar is boiled to obtain crystallized form	
Required drying time		
Required drying temperature	°C	°C

Tea

Initial Moisture Content:	60-80 %	
Final Moisture Content:	25-30 %; 3 % ??	
Energy Required (MJ/kg):	1.203	
Maximum Temperature:	140 °C	
Storage		
Drying Methods	**Low Temperature**	**High Temperature**
	1. sun drying 2. batch or in-bin drying with wood or crop waste burned for heat 3. solar drying	4. withering – uses warm air 5. fermentation – moist air at 95 % RH 6. tray dryer or fluidized bed dryer for drying by hot air
Required drying time	1. Several days 2. several hours 3. several hours	4. 16-20 hours 5. 1-2 hours 6. 24-26 minutes
Required drying temperature	30-60 °C	4. 35 °C 5. 25-30 °C 6. 100-140 °C

Tobacco Leaves

Initial Moisture Content:	70-85 %	
Final Moisture Content:	11-25 %	
Energy Required (MJ/kg):	1.592 – 1.997	
Maximum Temperature:	70 °C	
Storage		
Drying Methods	**Low Temperature**	**High Temperature**
	1. sun-drying 2. batch or in-bin drying with wood or diesel fuel burned	Batch drying with diesel fuel
Required drying time	1. several weeks (30 – 40 days) 2. several days to several weeks (15- 20 days)	Several hours
Required drying temperature	30-60 °C	18-75 °C

Tomatoes

Initial Moisture Content:	75 %	
Final Moisture Content:	35 %, < 4 % (powder)	
Energy Required (MJ/kg):	0.963	
Maximum Temperature:		
Storage	Opaque, air-tight containers (drums or packages), sometimes with a desiccant	
Drying Methods	**Low Temperature**	**High Temperature**
	1. sun-drying 2. drum drying for powder 3. vacuum dehydration for concentrated juices and sauces 4. plates heated with hot water under vacuum (powder)	After boiling: 1. conduction 2. tunnel spraying in hot air (powder)
Required drying time		1/50 s
Required drying temperature	30-60 °C	95 °C

Wheat

Initial Moisture Content:	15-20 %	
Final Moisture Content:	13-14 %	
Energy Required (MJ/kg):	0.055 – 0.193	
Maximum Temperature:	43 °C for mc > 24 % 49 °C for mc < 24 % 60 °C for grains to be milled if mc > 25 % 66 °C for grains to be milled if mc < 25 % 120 °C for grain for feed	
Storage	In silos without aeration and circulation In silos with sufficient aeration In ventilated storage bags	
Drying Methods	**Low Temperature**	**High Temperature**
	Shallow batch dryer (2.4 – 6 m³/min/m²) De-central in storage driers (silos, floor)	De-central batch dryers at farms or central large-scale continuous process at drying facility
Required drying time	Days-weeks; drying during storage	Minutes; drying and storage separately
Required drying temperature	45 °C	60 – 250 °C

Wood

Initial Moisture Content:	40-200 %	
Final Moisture Content:	8-10 %	
Energy Required (MJ/kg):		
Maximum Temperature:	60 °C	
Storage	Stacked; protected from the elements; in environment in which it is to be used	
Drying Methods	**Low Temperature**	**High Temperature**
	Air dry	Kiln dry
Required drying time	Several months	Several weeks
Required drying temperature	Ambient	

Further drying specifications in short

Product [6]	Humidity (water content %)		Drying temperature (°C)	Pre-treatment
	initial	final		
Beans	70	5	75	whitening
Cion	-	9	-	-
Copra	30	5	-	cutting
Corn	25	13	68-80	-
Legumes	80	10	-	cutting
Onions	80	4	55	cutting
Peanuts	40	9	-	-
Peas	80	5	65	whitening
Yams	75	7	75	cutting

Further aspects of drying

Drying principles and general considerations [7-9]

The main purpose of dehydration is to extend the shelf life of foods by a reduction in water activity, a_w. This will inhibit microbial growth, however the processing temperature will not normally be sufficient to cause inactivation, thus care will needed to be taken with the product on subsequent rehydration.

Water Activity

Water plays an important role in the stability of fresh, frozen and dried foods. It acts as a solvent for chemical, microbiological and enzymatic reactions. The water activity, a_w, is a measure of the availability of water to participate in such reactions. The water in a food will exert a vapour pressure. The extent of this pressure will depend on the amount of water present, the temperature and the composition of the food. Different food components will lower the water vapour pressure to different extents, with salts and sugars being more effective than larger molecules than starches or proteins. Thus two different foods with similar moisture contents may not necessarily have the same a_w. Water activity can be defined as the ratio of the vapour pressure exerted by the food to the saturated vapour pressure of water at the same temperature.

$$a_w = \frac{\text{Vapour pressure of water exerted by food}}{\text{Saturated vapour pressure of water at the same temperature}}$$

Values range from 0 for dried foods to 1.0 for foods such as milk, fresh fruit where the water is readily available. There is a relationship between a_w and RH of the form.

$$a_w = \frac{RH}{100}$$

The easiest way of determining a_w is to place the food into a sealed container, and to measure the relative humidity of the air in the container once equilibrium has been achieved. Thus it can be seen that the sorption isotherm is extremely useful because it also gives the relationship between the water activity and the moisture content. Thus it is possible to evaluate the lowest possible moisture content attainable at specified conditions of temperature and relative humidity and the a_w of the dehydrated product. In addition many spoilage reactions are influenced by a_w.

When certain solutes are added to foods, they lower the water activity by depressing the water vapour pressure. The extent of the depression can be calculated using Raoult's Law which states that the partial pressure p_A of a component over a solution is the product of the vapour pressure p_A^S of that component and the mole fraction □$_A$ of that component A.

$$p_A = \hat{x}_A \cdot p_A^S$$

Unfortunately food systems are not ideal, and are often too concentrated for this to occur and a_w depressions have to be discovered experimentally. Solutes that lower the water activity are known as humectants; for example salt, sugar, polyhydric alcohols such as glycerol and sorbitol. To complicate matters there are also hygroscopic compounds (where partial pressure varies with moisture content) and non-hygroscopic (constant vapour pressure at all moisture contents).

Moisture Content

Convention dictates that moisture contents of goods are usually measured on a wet basis, ie the mass of moisture per unit mass of wet grain and written as

$$x = \frac{\text{mass of water}}{\text{mass of water} + \text{mass of dry solids}} = \frac{m_W}{m_W + m_C^D} \quad [\%wb] \text{ or } \left[\frac{\text{kg water}}{\text{kg wet grain}}\right].$$

The alternative measure refers to the measurement on a dry basis:

$$X = \frac{\text{mass of water}}{\text{mass of dry solids}} = \frac{m_W}{m_C^D} \quad [\%db] \text{ or } \left[\frac{\text{kg water}}{\text{kg dry grain}}\right]$$

which is the mass of moisture per unit mass of completely dry crop. It can be shown by eliminating the mass of solids that

$$x = \frac{X}{1+X} \text{ or } X = \frac{x}{1-x}.$$

Moisture content x [%wb] is most often used in food composition tables, whereas moisture X [%db] is more often encountered with sorption isotherms and drying curves.

The mass of water lost from wet grain during drying can be calculated using the equation:

$$m_W = m_C^D \frac{x_i - x_e}{100 - x_e} \quad [\text{kg}]$$

with the initial moisture content x_i and the final or equilibrium moisture content x_e , both in [%wb]; or by using moisture in terms of [%db]:

$$m_W = m_C^D \cdot (X_i - X_e) \quad [\text{kg}].$$

Air Properties

For effective drying, air should be HOT, DRY and MOVING. These factors are inter-related and it is important that each factor is correct (for example, cold moving air or hot, wet moving air are each unsatisfactory).

The relationship between temperature, humidity and other thermodynamic properties of air is represented by a psychrometric or *Mollier* chart as shown in Fig. 0-1.

It is important to appreciate the difference between the absolute humidity and relative humidity of air. The **absolute humidity** X^A is the moisture content of the air (mass of water per unit mass of air, e.g. g/kg) whereas the **relative humidity** (RH) is the ratio, expressed as a percentage, of the moisture content of the air at a specified temperature to the moisture content of air if it were saturated at that temperature.

So 0% RH is completely dry air and 100% RH is air that is fully saturated with water vapour.

Low RH (or dry) air must be blown over foods so that it has the capacity to pick up water vapour from the food and remove it. If high RH (or wet) air is used it quickly becomes saturated and can not pick up further water vapour from the food.

The temperature of the air affects the humidity (higher temperatures reduce the humidity and allow the air to carry more water vapour).

Note that there are two types of air temperature:
The temperature of the air, measured by a thermometer bulb, is termed the **dry-bulb temperature.**

If the thermometer bulb is surrounded by a wet cloth, heat is removed by evaporation of the water from the cloth and the temperature falls (to the **'wet bulb' temperature**). The difference between the two temperatures is used to find the relative humidity of air of the psychrometric chart.

The **dew point** is the temperature at which air becomes saturated with moisture (100% RH) and any further cooling from this point results in condensation of the water from the air. This is seen at night when air cools and water vapour forms as dew on the ground.

Adiabatic cooling lines are the parallel straight lines sloping across the chart, which show how absolute humidity decreases as the air temperature increases.

The psychrometric chart is useful for finding changes to air during drying and hence the efficiency of a drier. The following examples show how it is used.
Using Fig. 0-1, find:

1. the absolute humidity of air which has 50 % RH and a dry-bulb temperature of 60 °C
2. the wet-bulb temperature under these conditions
3. the RH of air having a wet-bulb temperature of 45 °C and a dry-bulb temperature of 75 °C
4. the dew point of air cooled adiabatically from a dry-bulb temperature of 55 °C and 30 % RH
5. the change in RH of air with a wet-bulb temperature of 39 °C, heated from a dry-bulb temperature of 50 °C to a dry-bulb temperature of 80 °C
6. the change in RH of air with a wet-bulb temperature of 35 °C, cooled adiabatically from a dry bulb temperature of 70 °C to 40 °C.

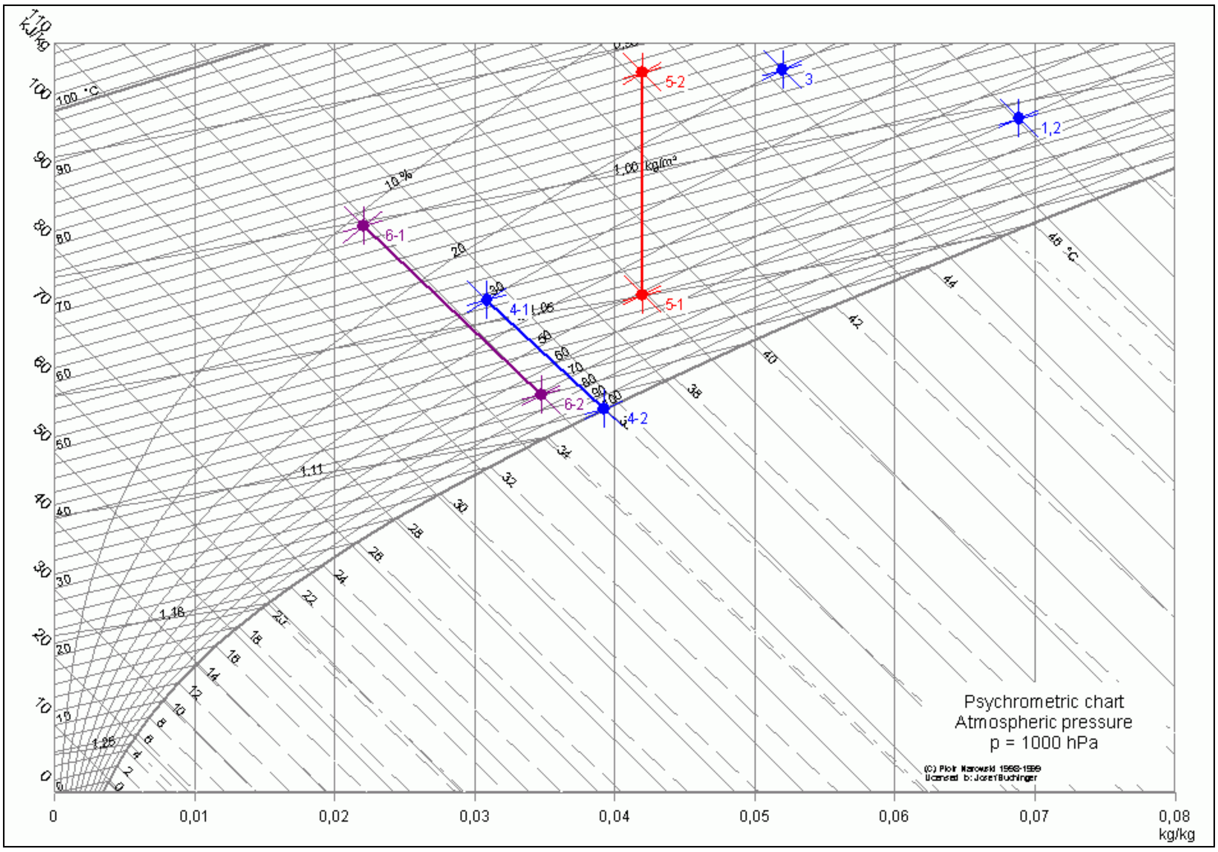


Fig. 0-1: Psychrometric chart (Mollier-Chart) with example points.

Answers

1. X^A= 0.068 kg per kilogram of dry air (find the intersection of the 60 °C and 50 % RH lines, and then follow the chart vertically down to read off the absolute humidity)
2. 46.5 °C (from the intersection of the 60 °C and 50 % RH lines, move left parallel to the wet bulb lines to read off the wet-bulb temperature)
3. 20 % (find the intersection of the 45 °C and 75 °C lines and follow the sloping RH line downwards to read off the % RH)
4. 36 °C (find the intersection of the 55 °C and 30 % RH lines and follow the wet-bulb line down until the RH reaches 100 %)
5. 50-13 % (find the intersection of the 39 °C wet-bulb and the 50 °C dry-bulb temperatures, and follow the vertical line to the intersection with the 80 °C dry-bulb line; read the sloping RH line at each intersection (this represents the changes that take place when air is heated prior to being blown over food))
6. 10-70% (find the intersection of the 35 °C wet-bulb and 70 °C dry-bulb temperature, and follow the wet-bulb line down until the intersection with the 40 °C dry-bulb line; read sloping RH line at each intersection (this represents the changes taking place as the air is used to dry food; the air is cooled and becomes more humid as it picks up moisture from the food).

The heating of air from temperature T_A to T_B is represented by the line 'AB' (red line in Fig. 0-2). During heating the absolute humidity remains constant at X_A^A ($X_A^A = X_B^A$) whereas the relative humidity falls from RH_A to RH_B. As air moves through the grain bed it absorbs moisture. Under (hypothetical) adiabatic drying sensible heat in the air is converted to latent head and the change in air conditions is represented along a line of constant enthalpy, 'BC'. The air will have increased in both absolute humidity, H_C, and relative humidity, RH_C, but fallen in temperature, T_C. The absorption of moisture by the air would be the difference between the absolute humidities at 'C' and 'A' (X_C^A - X_A^A).

If unheated air was passed through the bed the drying process would be represented along the line 'AD'. Assuming that the air at 'D' was at the same relative humidity, RH_C, as the heated air at 'C' then the absorbed moisture would be (X_D^A - X_A^A), considerably less than that absorbed by the heated air (X_C^A - X_A^A).

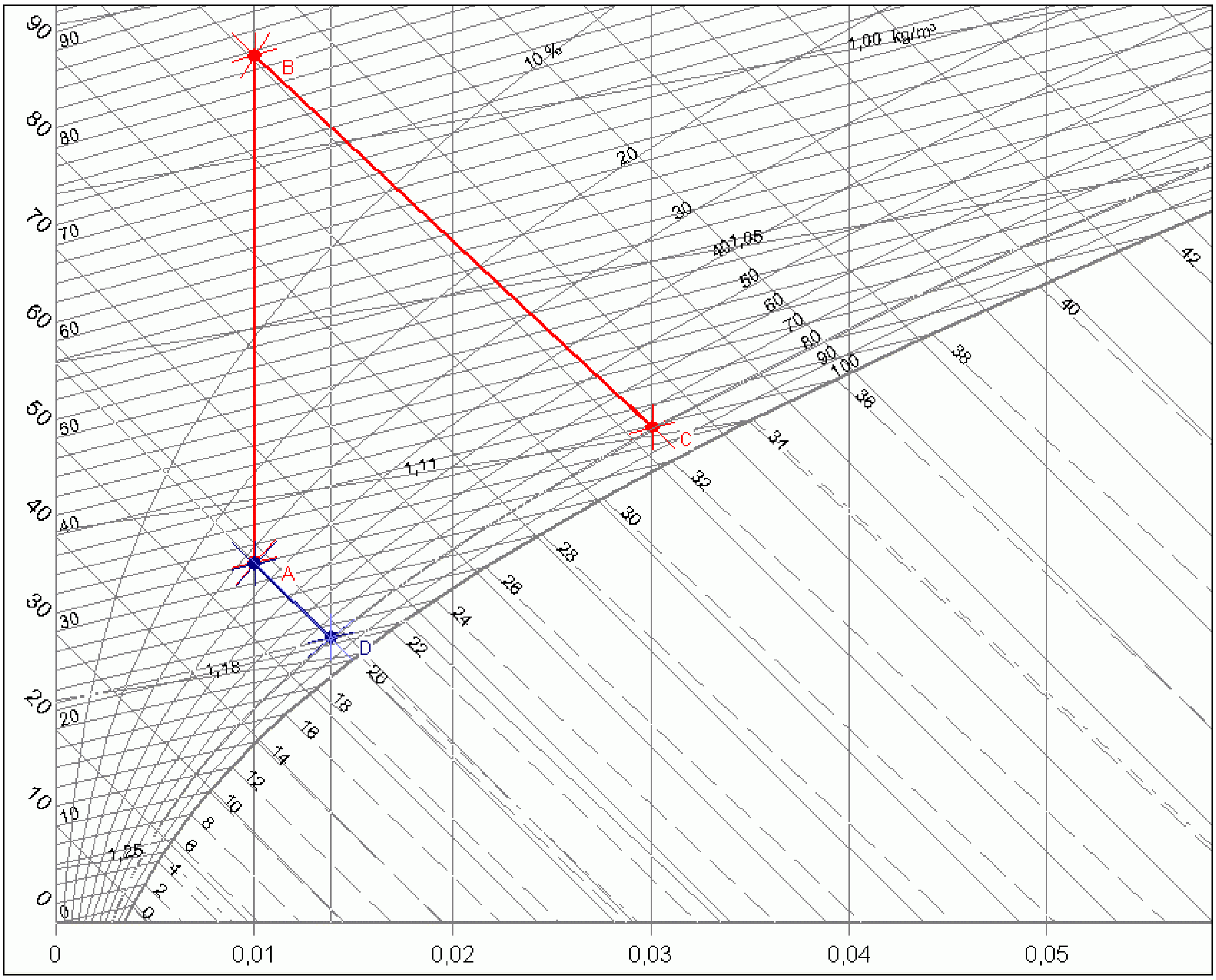


Fig. 0-2: Part of a Mollier-chart showing processes of drying with pre-heating (red) and without (blue):

Drying Mechanisms

There are two basic mechanisms involved in the drying process; the migration of moisture from the interior of an individual grain to the surface, and the evaporation of moisture from the surface to the surrounding air. The rate of drying is determined by the moisture content and the temperature of the grain and the temperature, the (relative) humidity and the velocity of the air in contact with the grain.

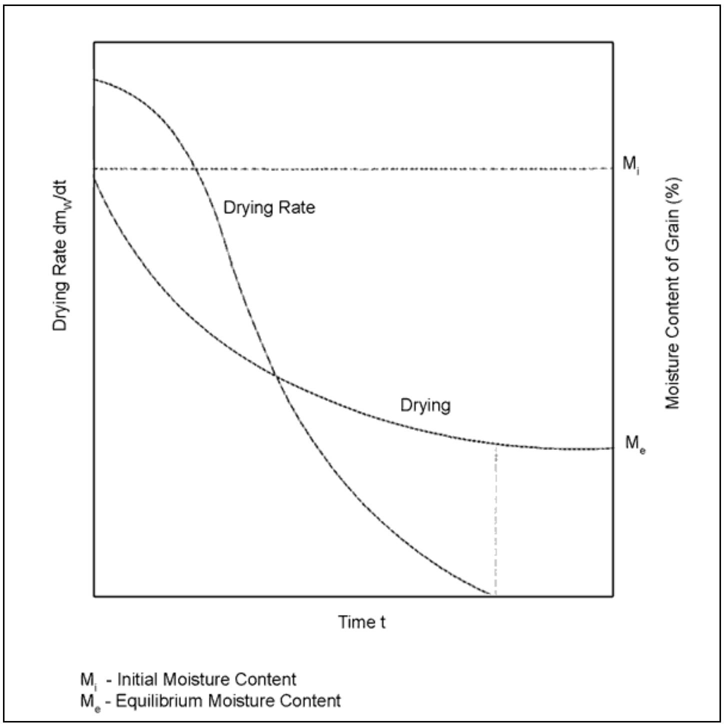


Fig. 0-3: Drying and drying rate curves.

Fig. 0-3 demonstrates the drying of a single layer of grain exposed to a constant flow of air. The moisture content falls rapidly at first but as the grain loses moisture the rate of drying slows. In general the drying rate decreases with moisture content; increases with increase in air temperature; or decreases with increase in air humidity. At very low air flows increasing the velocity causes faster drying but at greater velocities the effect is minimal indicating that moisture diffusion within the grain is the controlling mechanism.

If a new type of drier is to be used, or if a different type of food is to be dried, it is necessary to do some experiments to find the rate of drying. The information can then be used to find the time that the food should spend in the drier before the moisture content is low enough to prevent spoilage by micro-organisms. The rate of drying also has an important effect on the quality of the dried foods and (in artificial driers) the fuel consumption.

For a simplified method of drying rate determination you will need a clock/watch and a set of scales. Food is weighed, placed in the drier and left for 5 –10 minutes. It is then removed, reweighed and replaced. This is continued until the weight of the food no longer changes. The interval between weighing can be increased when the changes in weight start to become less. You should also make a note of the wet and dry bulb temperatures of the air inside the drier and the air outside. The results are plotted on a graph. The simplified approach assumes two distinct phases of drying - the 'constant' and ‘falling’ rate periods, Fig. 0-4.

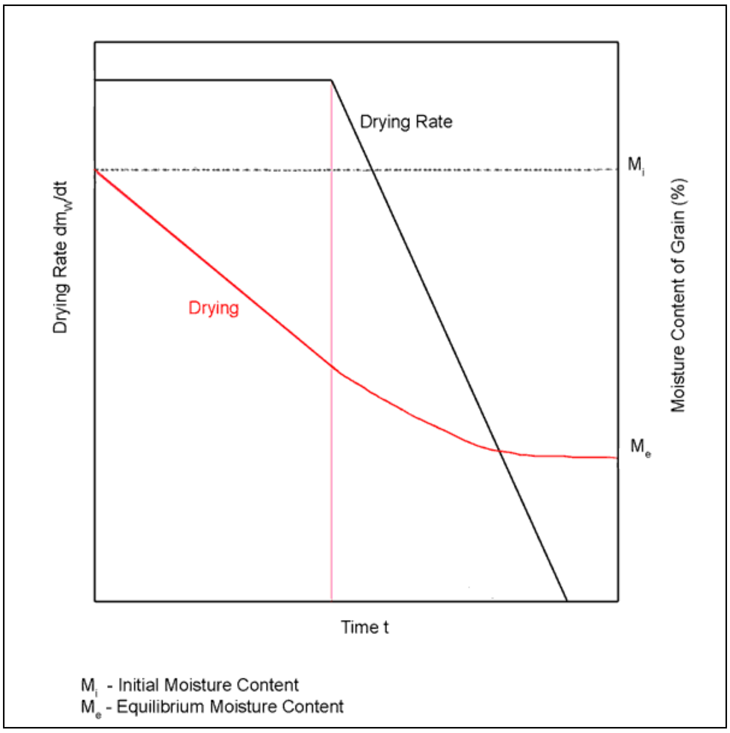


Fig. 0-4: Ideal drying and drying rates.

In the constant rate the surface of the food remains wet and it can therefore be spoiled by moulds and bacteria. In the falling rate the surface is dry and the risk of spoilage is much smaller. The food should therefore be dried to a weight that corresponds to the end of the constant rate period as quickly as possible (however see 'case hardening' below).

Drying rate can be calculated for each 10 minute period as follows:

$$\text{Drying rate} = \frac{\text{initial weight - final weight}}{\text{time interval (eg 10 minutes)}} \text{ [g/s], [kg/hr]}$$

The moisture content of both the fresh food and the final dried food can be found by weighing the food, heating at 100°C in an oven for 24 hours and reweighing. The moisture content x (%wb) is found as follows:

$$x = \frac{\text{initial weight - final weight}}{\text{initial weight}} 100 \left[\%\text{wb}\right]$$

Other values of moisture content during the drying period can be found by relating these two results to the weights of food recorded during the drying experiment and applying similar factors to intermediate weights. Fig. 0-4 gives two important pieces of information:

1. The actual drying rate during the constant rate period which shows how efficient the drier is.
2. The final moisture content of the dried food which shows whether it will be stable during storage.

Typically, a drying rate of 0.25 kg/hr would be expected for solar driers depending on the design and climate, and 10-15 kg/hr for artificial driers.

If the drying rate is lower than this, the air temperature or speed is too low and/or the RH is too high. This can be checked by the temperature measurements made during the experiment and by using the psychrometric chart. Normally the air in the drier should be 10-

15 ºC above room temperature in solar driers and 60-70 ºC in artificial driers. The RH of air entering the drier will vary according to local conditions, but should ideally be below about 60 % RH.

Grains are hydroscopic and will lose or gain moisture until equilibrium is reached with the surrounding air. The equilibrium moisture content (EMC) is dependent on the relative humidity and the temperature of the air; EMCs for a range of grains are shown in Table 0-1.

Table 0-1: Grain Equilibrium Moisture Contents[3] (BROOKER et.al., 1974)

Grain	Relative Humidity (%)							
	30	40	50	60	70	80	90	100
	Equilibrium Moisture Content x_e [%wb] at 25 °C							
Barley	8.5	9.7	10.8	12.1	13.5	15.8	19.5	26.8
Shelled Maize	8.3	9.8	11.2	12.9	14.0	15.6	19.5	26.8
Paddy	7.9	9.4	10.8	12.2	13.4	14.8	16.7	/
Milled Rice	9.0	10.3	11.5	12.6	12.8	15.4	18.1	23.6
Sorghum	8.6	9.8	11.0	12.0	13.8	15.8	18.8	21.9
Wheat	8.6	9.7	10.9	11.9	13.6	15.7	19.7	25.6

It is very important to appreciate the practical significance of the EMC. Under no circumstances is it possible to dry to a moisture content lower than the EMC associated with the temperature and humidity of the drying air; for example, the data in Table 0-1 show that paddy can only dry to a moisture content of 16.7% when exposed to air at 25°C and 90% relative humidity. If paddy at moisture content less than 16.7% is required then either the temperature of the drying air has to be increased or its humidity reduced.

The drying of grains in thin layers where each and every kernel is fully exposed to the drying air can be represented in the form:

$$MR = f(T, RH, t) \qquad \text{Equ. (1)}$$

where

$$MR = \frac{X - X_e}{X_i - X_e} \text{ (the moisture ratio);} \qquad \text{Equ. (2)}$$

X is the moisture content of the grain at any level and at any time [%db];
X_e is the equilibrium moisture content [%db];
X_i is the initial moisture content of the wet grain [%db];
T is the air temperature (°C);
RH is the air relative humidity (%); and
t is the drying time (s).

Empirical data have been used to determine mathematical approximations of the relationship between drying rate and air conditions. Relationships for many grains have been summarized by Brook & Foster (1981). For example, a thin layer equation for paddy (Teter 1987) is:

$$MR = \exp(-A * t^B) \qquad \text{Equ. (3)}$$

[3] Brooker D B. Bakker-Arkema F W and Hall C W (1974). Drying Cereal Grains. Westport: Avi Publishing Co. Inc. 265 pp.

Where
A = 0.026 - 0.0045·RH + 0.01215·T; and
B = 0.013362 + 0.194·RH - 0.000177·RH^2 + 0.009468·T,
with RH expressed as a percentage, and T in °C.

In the drying of grain in a deep bed, whilst individual kernels may all be losing moisture at different rates, the overall drying rate will remain constant for a long period. The air absorbs moisture as it moves through the bed until it becomes effectively saturated and moves through the remaining layers of grain without effecting further drying.

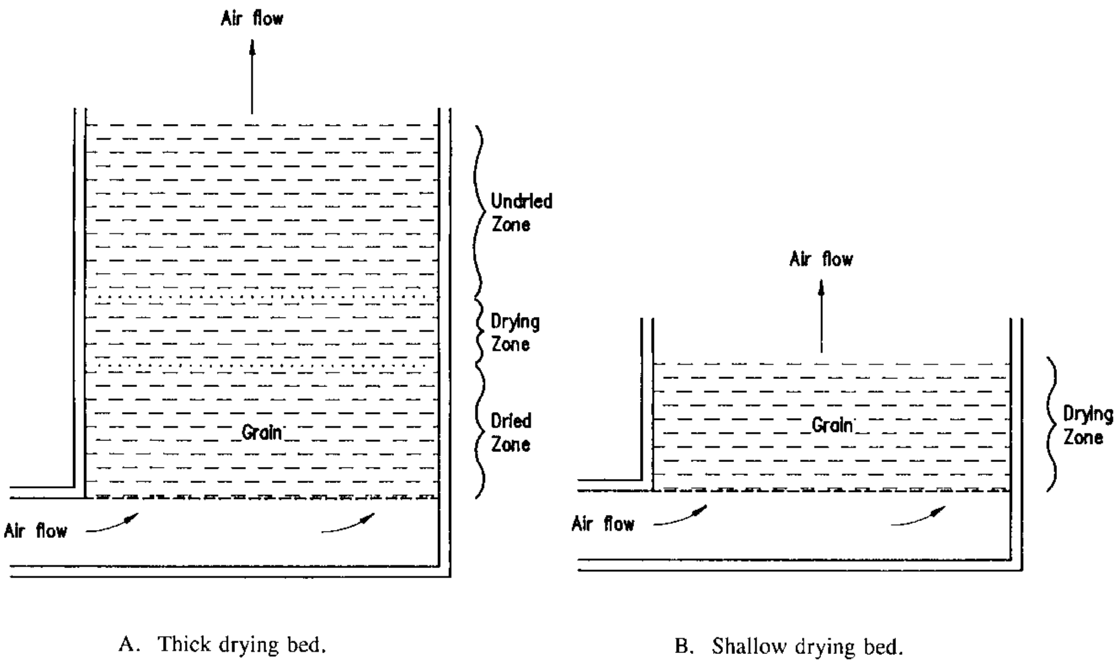


Fig. 0-5: Drying zone in fixed-bed drying.[9]

Fig. 0-5 shows the three zones present within a thick drying bed at an intermediate time within the drying operation. Drying takes place within a discrete zone, the size of which depends on the moisture content of the grain and the temperature, humidity and velocity of the air. Below the drying zone is the dried zone where the grain is in equilibrium with the air. Above the drying zone is the un-dried zone wherein the grain remains unchanged from its initial condition. In a shallow bed as in Fig. 0-5 B the drying zone is thicker than the bed depth and drying would occur initially throughout the bed.

The change in temperature and humidity of air as it moves through a bed of grain depends on the rate at which moisture is being evaporated from each kernel as an individually exposed element. Knowledge of the effect of grain moisture content, other grain properties, the temperature, humidity and flow rate of the air upon fully exposed kernels is essential to an understanding of how drying would proceed within a bed.

Unfortunately no theory has been developed that accurately and practically describes the thin layer drying rate. As described above many empirical relationships have been established and these have to be used in prediction of drying time (see below). Accurate prediction of drying time is further inhibited by the variability of key factors encountered in practice, particularly so for the simple drying systems that are the most appropriate for use in developing countries. For example the moisture content of individual grains is likely to vary considerably within a batch and in the case of drying with a heater of constant heat output the temperature of the drying air will vary with changes in ambient air temperature.

Estimation of Drying Time

A basic design procedure for the field worker is best illustrated for the design of a batch type dryer, although the principles can be applied to a certain extent in the design of continuous multi-stage systems.

Assumed ambient air conditions are a dry bulb temperature of T_A and a relative humidity of RH_A; from the psychrometric chart the wet bulb temperature, $T_{A,W}$, the enthalpy, H_A, and the absolute humidity x_A can be derived. The air is heated to a selected safe drying temperature, T_B, thereby raising the enthalpy of the air to x_B.

The wet grain of equivalent bone-dry mass m_G has a moisture content of X_W [%db] and is to be dried to a moisture content of X_D [%db]. A mass air flow of V is available.
The moisture, m_W, to be removed,

$$m_W = m_G * (X_i - X_D) \qquad \text{Equ. (4)}$$

It is assumed that throughout the drying period the air will exhaust from the bed at a constant wet bulb temperature and in equilibrium with the uppermost layers of grain. Initially the exhaust air will be in equilibrium with grain at X_i moisture and finally in equilibrium with grain at X_e moisture. By superimposing equilibrium moisture content data on to the psychrometric chart for the initial and final moisture contents the humidity of the exhaust air at the beginning and end of drying can be found. An average of the initial and final exhaust air relative humidities, $RH_{i,e}$ is taken for calculation of drying time, t_D:

$$t_D = \frac{m_W}{V(RH_e - RH_{i,e})}$$

More rigorous approaches to the design of drying systems have been developed. These include the methods based on thin layer drying equations described by Brook & Foster (1981) and Brooker et al. (1974). Many of these have been developed into sophisticated simulation techniques (Brooker et al. 1974).

Drying Efficiency

The efficiency of the drying operation is an important factor in the assessment and selection of the optimum dryer for a particular task. There are three groups of factors affecting drying efficiency:

- those related to the environment, in particular, ambient air conditions;
- those specific to the crop;
- those specific to the design and operation of the dryer.

There are several different ways of expressing the efficiency of drying, of which the sensible heat utilization efficiency (SHUE), the fuel efficiency, and the drying efficiency are the most useful.

The SHUE takes into account the sensible heat attributable to the condition of the ambient air and any heat added to the air by the fan as well as the heat supplied by combustion of the fuel. It is defined as:

$$SHUE = \frac{\text{Heat Utilized for Moisture Removal}}{\text{Total Sensible Heat in the Drying Air}}$$

The fuel efficiency is based only on the heat available from the fuel:

$$\text{Fuel Efficiency} = \frac{\text{Heat Utilized for Moisture Removal}}{\text{Heat Supplied from Fuel}}$$

It can be appreciated that the fuel efficiency would be significantly different for the operation of the same dryer at two locations with widely different ambient conditions. With low temperature drying, particularly in dry climates, the heat supplied from the fuel may be less than half of the total sensible heat and the fuel efficiency may exceed 100%. Direct comparison of the performance of dryers at separate locations is not possible using the fuel efficiency.

The drying efficiency, defined as:

$$\text{Drying Efficiency} = \frac{\text{Heat Utilized for Moisture Removal}}{\text{Heat Available for Moistrue Removal}}$$

is the expression to be used for evaluation of dryer designs or comparison between dryers, since it is a measurement of the degree of utilization of the sensible heat in the drying air.
Foster (1973) evaluated the fuel and drying efficiencies of several types of dryers used with maize. Over a wide range of conditions, continuous-flow dryers were found to have a fuel efficiency of 38% and a drying efficiency of 51%, batch dryers 42% and 58%, dryeration 61% and 78%, and two-stage drying, 60% and 79%, respectively.

Physical Properties of Grain

Comprehensive data on the numerous physical and thermal properties of grain are available in texts such as Brooker et al. (1974) and Brook & Foster (1981).

Bulk Density

The bulk density of grain is the weight per unit volume. Moisture content has an appreciable effect on the bulk density.

Resistance to Air Flow

The energy required to force air through a bed of grain is dependent on the air flow, the grain depth and physical properties of the grain such as surface and shape factors, the kernel size distribution, moisture content, and the quantity and nature of contamination, stones, straw, weeds etc.

The relation between air flow and the pressure drop generated across the bed for selected grains is illustrated in Fig. 0-6. The data generally refer to clean and dry grain and correction factors of up to 1.4 are used for very wet and dirty grain (Teter 1987).

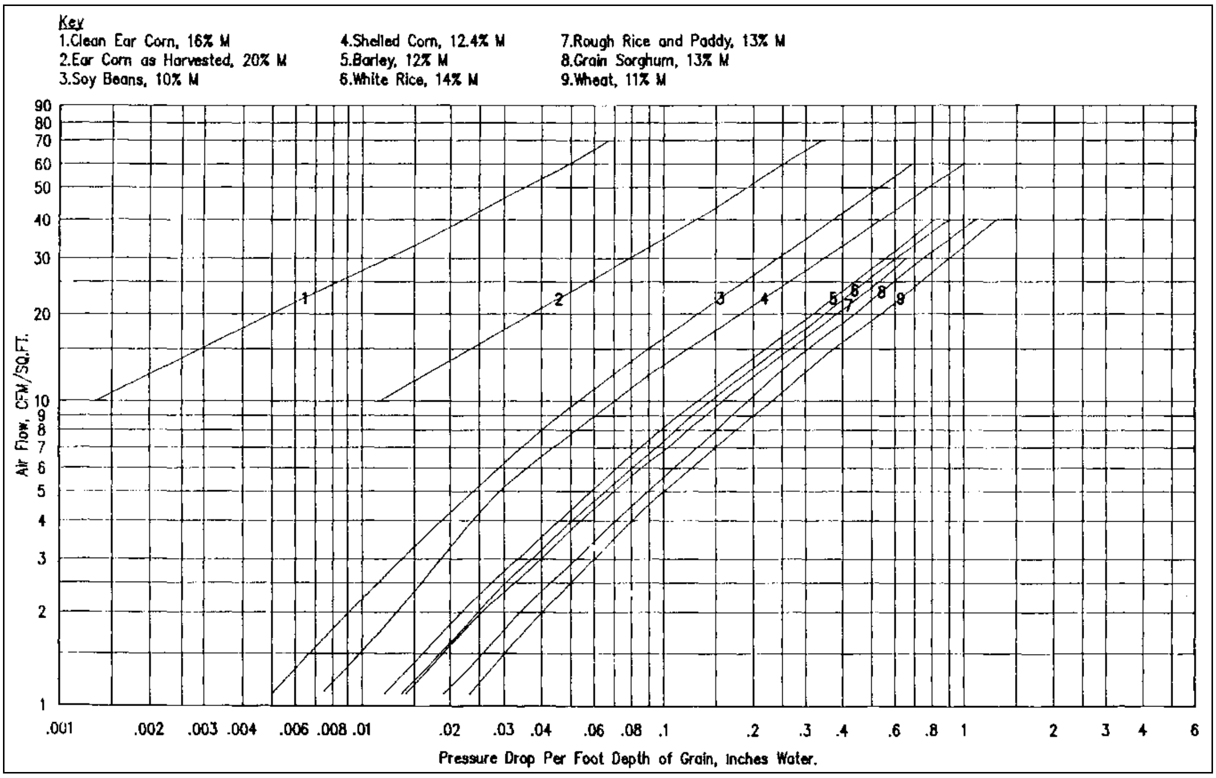


Fig. 0-6: Resistance of Grains and Seeds to Air Flow.[9]

Effect of Drying on Grain Quality

The drying operation must not be considered as merely the removal of moisture since there are many quality factors that can be adversely affected by incorrect selection of drying conditions and equipment. The desirable properties of high-quality grains include:

- low and uniform moisture content;
- minimal proportion of broken and damaged grains;
- low susceptibility to subsequent breakage;
- high viability;
- low mould counts;
- high nutritive value;
- consumer acceptability of appearance and organoleptic properties.

Moisture Content

It is essential that the grain after drying is at a moisture content suitable for storage. As discussed the desired moisture content will depend on the type of grain, duration of storage, and the storage conditions available. It is also important that the drying operation is carried out to minimize the range of moisture levels in a batch of dried grain. Portions of under-dried grain can lead to heating and deterioration.

Stress Cracking and Broken Grains

Drying with heated air or excessive exposure to sun can raise the internal kernel temperature to such a level that the endosperm cracks. The extent of stress cracking is related to the rate of drying. Rapid cooling of grain can also contribute to stress crack development.

Nutritive Value

Grain constituents such as proteins, sugars and gluten may be adversely affected when the grain attains excessive temperatures. The feeding value of grains can be lowered if inadequately dried.

Grain Viability

Seed grain requires a high proportion of individual grains with germination properties. The viability of grain is directly linked to the temperature attained by grains during drying (Kreyger 1972).

Case hardening

Case hardening is the formation of a hard skin on the surface of fruits, fish and some other foods which slows the rate of drying and may allow mould growth. It is caused by drying too quickly during the initial (constant rate) period and can be prevented by using cooler drying air.

Mould Growth

Many changes in grain quality are linked to the growth of moulds and other microorganisms. The rate of development of microorganism is dependent on the grain moisture content, grain temperature, and the degree of physical damage to individual grains. Mould growth causes damage to individual grains resulting in a reduction in value. Under certain circumstances mycotoxin development can be a particular hazard.

Appearance and Organoleptic Properties

The colour and appearance as perceived by the customer and/or consumer. For example, the colour of milled rice can be adversely affected if the paddy is dried with direct heated dryers with poorly maintained or operated burners or furnaces.

Food preparation and treatment

The colour of many fruits can be preserved by dipping in a solution of 0.2-0.5% sodium metabisulphite or by exposing to sulphur dioxide in a sulphuring cabinet, Fig. 0-7.

Vitamin losses are often greater during peeling/slicing etc than during drying. Loss of fat soluble vitamins can be reduced by shade drying and loss of water soluble vitamins by careful slicing using sharp knives. Blanching of vegetables is necessary before drying and water soluble vitamins are also lost in this stage. It should be noted that dried food does not destroy micro-organisms and only inhibits their growth.

So heavily contaminated fresh food will become heavily contaminated dried and rehydrated food. Blanching is one method of reducing the levels of initial contamination. Thorough washing of fresh foods should be done routinely before drying.

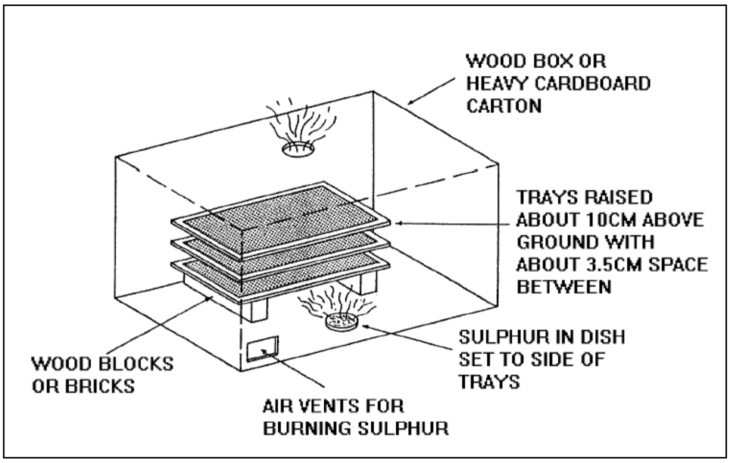


Fig. 0-7: Sulphuring Cabinet.

The stability of a dried food during storage depends on its moisture content and the ease with which the food can pick up moisture from the air. Clearly the risk of moisture pick up is greater in regions of high humidity. However, different foods pick up moisture to different extents (compare for example the effect of high humidity on salt or sugar with the effect on pepper powder -salt and sugar pick up moisture, pepper doesn't).

For foods that readily pick up moisture it is necessary to package them in a moisture proof material.

Low moisture content is only an indication of food stability and not a guarantee. It is the availability of moisture for microbial growth that is more important and the term 'Water Activity' (AW) is used to describe this. Water Activity varies from 0-1.00 and the lower the value the more difficult it is for micro-organisms to grow on a food.

Examples of moisture contents and AW values for selected foods and their packaging requirements are shown in Table 0-2.

Table 0-2: Food type characteristics and packaging requirements.

Food	Moisture Content %	Water activity	Degree of protection required
Fresh meat	70	0.985	Package to prevent moisture loss
Bread	40	0.96	
Rice	15-17	0.80	Minimum protection or no packaging required
Wheat flour	14.5	0.72	
Raisins	27	0.60	
Nuts	18	0.65	
Spices	5-8	0.50	Package to prevent moisture uptake
Dried vegetables	5	0.20	

Glossary of Terms [10]

AC (Alternating Current): Electric current in which the direction of the flow is reversed at frequent intervals, 100 times per second in the Philippines (50 cycles per second). The current coming from household electric sockets is normally of this type.
B.t.u.: British thermal unit
Biomass briquetting: Making compressed blocks from loose biomass materials, e.g. ricehusk, saw dust etc.
Biomass: Matter constituting and originating from living beings.
British thermal unit (BTU): The amount of heat required to raise the temperature of 1 pound of water at its maximum density, 1°F.
C. wt.: Current weight
C.O.D. Wt.: Calculated ovendry weight
Casehardening: A condition of stress and set in dry wood in which the outer fibers are under compressive stress and the inner fibers under tensile stress, the stresses persisting when the wood is uniformly dry.
Commercial energy: Literally, energy traded in the market for a monetary price, usually conventional energy, such as coal or oil, but also wood energy, which is traded in urban and semi-urban areas in many developing countries. Often used to refer to conventional fuels, such as coal, gas and electricity, thus ignoring commercially traded woodfuels. The term non-commercial energy is often used to refer to biomass energy, ignoring the commercial trade of woodfuels and other biomass fuels.
Conditioning: In kiln drying, a process for relieving the stresses present in the wood at the end of drying. Consists of subjecting the stock while still in the kiln to a fairly high dry-bulb temperature and an eqilibrium moisture content condition 3 to 4 percent above the desired average moisture content for the stock. The process should be of sufficient duration to eliminate casehardening through the reduction of compression and tension sets.
Conventional energy: Fossil-based fuels, such as oil, coal, natural gas and their derivatives, for which large-scale mechanism for exploration, conversion and distribution exist.
D.B.: Dry bulb
DC (Direct Current): Electricity that flows continuously in one direction as contrasted with alternating current (AC). DC is required by many electronic devices; batteries and solar cells produce DC.
Decay: The softening, weakening, or total decomposition of produce substance by fungi.
Depression, wet-bulb: The difference between the dry- and wet-bulb temperatures.
Diffusion: Spontaneous movement of water through produce from points of high concentration to points of low concentration.
Diffusivity: The measure of rate of moisture movement through produce as a result of differences in moisture content.
Discoloration: Change in the colour of produce due to fungal and chemical stains, weathering, or heat treatment.
Dry kiln: A room, chamber, or tunnel in which the temperature and relative humidity of air circulated through parcels of lumber, veneer, and other wood products can be controlled to govern drying conditions.
Dryer: Air moving and directing equipment used to accelerate the air drying of produce.
Drying rates: The loss of moisture from lumber or other wood products per unit of time. Generally expressed in percentage of moisture content lost per hour or per day.
Drying record: A daily or weekly tabulation of dryer or kiln operation including sample weight, MC, and temperature readings or recorder-controller charts.
Drying: The process of removing moisture from produce.
EMC: Equilibrium moisture content
Equalization and conditioning: In kiln drying the process of increasing the equilibrium moisture content condition in the final stages of drying lumber and other mill products to-(l)

reduce the moisture content range between boards, (2) flatten the moisture content gradient within boards, and (3) relieve drying stresses. Usually equalization and conditioning are two separate stages in final kiln drying.

Equilibrium moisture content: The moisture content at which wood neither gains nor loses moisture when surrounded by air at a given relative humidity and temperature. EMC is frequently used to indicate potential of an atmosphere to bring wood to a specific MC during a drying operation.

F.S.P.: Fibre saturation point

Free water: In wood technology, water that is held in the lumens or the grosser capillary structure of the wood.

Fungi: Low forms of plants consisting mostly of microscopic threads (hyphae) that traverse wood in all directions, dissolving materials out of the cell walls that they use for their own growth.

G. Wt.: Green weight

Greenhouse Effect (relating to buildings)**:** The characteristic tendency of some materials (such as glass) to transmit radiation of relatively short wavelengths (for example, sunlight) and block radiation of longer wavelengths (for example, radiation emitted by objects at relatively low temperatures) causing an accumulation of heat within the space enclosed by such a material.

Greenhouse Effect (relating to climate)**:** The warming of the earth due accumulation of certain trace gases (the so-called greenhouse gases) in the atmosphere.

Hardwoods: Generally one of the botanical groups of trees that have broad leaves in contrast to the conifers or softwoods. The term has no reference to the actual hardness of the wood.

High temperature dryers: High temperature dryers are necessary when very fast drying is desired. They are usually employed when the products require a short exposure to the drying air. Their operating temperatures are such that, if the drying air remains in contact with the product until equilibrium moisture content is reached, serious over drying will occur. Thus, the products are only dried to the required moisture contents and later cooled. High temperature dryers are usually classified into batch dryers and continuous flow dryers. In batch dryers, the products are dried in a bin and subsequently moved to storage. Thus, they are usually known as batch-in-bin dryers. Continuous-flow dryers are heated columns through which the product flows under gravity and is exposed to heated air while descending. Because of the temperature ranges prevalent in high temperature dryers, most known designs are electricity or fossil-fuel powered. Only a very few practically-realised designs of high temperature drying systems are solar-energy heated.[11] In kiln drying wood, use of dry-bulb temperatures of 212°F or more.

Humidity: The moisture content of air.

Hybrid System: An energy system that does not rely on only one source of energy, for example, wind- diesel, PV-diesel, wind-PV-diesel etc.

Hygroscopicity: The property of a stance, such as wood, which permit absorb and lose moisture readily.

Insolation: The intensity of solar radiation that strikes a surface, usually expressed as watts per square meter.

kgoe (kilogram of oil equivalent): A unit of energy, 1 kgoe H 12.82 kWh

Kiln: A chamber or tunnel used for drying and conditioning lumber, veneer, and other lood products in which the temperature and relative humidity of the circulated can be varied.

kW (kilowatt): A unit of power - one thousand watts.

kWh (kilowatt-hour): A unit of energy (power expressed in kW multiplied by time expressed in hours).

Losses, drying: In. drying products, the reduction in volume and grade quality that can be attributed to the drying process.

Low temperature dryers: In low temperature drying systems, the moisture content of the product is usually brought in equilibrium with the drying air by constant ventilation. Thus, they do tolerate intermittent or variable heat input. Low temperature drying enables crops to be dried in bulk and is most suited also for long term storage systems. Thus, they are usually known as bulk or storage dryers. Their ability to accommodate intermittent heat input makes low temperature drying most appropriate for solar-energy applications. Thus, some conventional dryers and most practically-realised designs of solar-energy dryers are of the low temperature type.[11]

Lumber: The product of the sawmill and planing mill not further manufactured than by sawing, resawing, passing lengthwise through a standard planing machine' cross cutting to length, and matching.

Boards: Yard lumber less than 2 inches thick and 1 or more 2 inches wide:

Common lumber: A classification of medium and low-grade hardwood lumber and/or softwood lumber suitable for general construction and manufacturing but not suitable for finish grade.

Dimension lumber: As applied to hardwood lumber, a term loosely used but generally referring to small squares or pieces of rectangular cross section used for furniture and like purposes (small dimension).

Dressed lumber: The dimensions of lumber after drying and surfacing with a plaining machine.

Finish lumber: A collective term for upper grades of lumber suitable for natural or stained finishes.

Flooring lumber: Generally, a grade of either hardwood or softwood boards that have been found to produce maximum quantity of flooring of the desired quality.

Nominal size: As applied to timber or lumber, the size other than the actual size, by which it is known and sold in the market.

Rough lumber: Lumber as it comes from the saw.

Structural lumber: Lumber that is nominally 2 or more inches thick and nominally 4 or more inches wide, intended for use where working stresses are required. The grading of structural lumber is based on the strength of the piece and the use of the entire piece, e.g., stud, joist, beam, plank, girder, rafters, franiing, etc.

Yard lumber: Lumber of all sizes and patterns that is intended for general building purposes. The grading of yard lumber is based on the intended use of the particular grade and is applied to each piece with reference to its size and length when graded, without consideration to further manufacture.

Moisture content: The amount of water contained in the wood, usually expressed as a percentage of the weight of the ovendry wood.

Average moisture content: The moisture content, in percent, of a single section representative of a larger piec6 of wood or the average of all the moisture content determinations made on a board or other wood item or of a number of determinations made on a lot of lumber or other wood products.

Final moisture content: The average moisture content of the lumber or other wood product at the end of the drying process. Initial moisture content. The moisture content of the wood at the start of the drying process.

In-use moisture content: The moisture content that wood items attain in the environmental conditions of usage.

Range: The difference in moisture content between the driest and wettest boards in a shipment, lot, kiln charge, etc., or between representative samples of the lot.

Moisture gradient: In lumber drying, the distribution in moisture content within the wood. During drying, the differences are between the low moisture content of the relatively dry surface layers and the higher moisture content at the center of the piece.

M.C.: Moisture content

Mould: A fungus growth on lumber or other wood products at or near the surface and, therefore, not typically resulting in deep discolorations. Mold is usually ash green to deep green in colour, although black and yellow are common.

MW (Megawatt): A unit of power - one million watts.

MWh (Megawatt-hour): A unit of energy - one megawatt of power for a period of one hour.

Natural convection: Flow of currents of a gas (or liquid) in a space due to the existence of temperature differences. Hot gas (or liquid) has a lower density and therefore moves up while colder gas (or liquid) moves down.

O.D. Wt.: Ovendry weight
Permeability: The ease with which a fluid flows through a porous material (wood) in response to pressure.
Pile: In air drying, stacking lumber layer by layer, separated by stickers or self stickering, on a supporting foundation (hand stacked). Also, stickered unit packages by lift truck or crane, one above the other on a :foundation and separated by bolsters.
Pre-drying: A wood drying process carried out in special equipment before kiln drying.
Primary energy: Energy form as it is available in nature.
Pyrolysis: Thermo-chemical conversion process that occurs when biomass is heated in the absence of air. The process breaks down biomass into a complex mixture of liquids, gases, and a residual char. If wood is used as the feedstock, the residual char is what is commonly known as charcoal.
R.H.: Relative humidity
Radiation: Transfer of energy across open space in the form of electromagnetic waves such as light.
Recorder-controller: An instrument that continuously records dry- and wet-bulb temperatures of circulated air and regulates these temperatures in a dryer or kiln by activating automatic heat and steam spray valves.
Relative humidity: Under ordinary temperatures and pressures, it is the ratio of the weight of water vapour in a given unit of air compared with the weight which the same unit of air is capable of containing when fully saturated at the same temperature. More generally, it is the ratio of the vapour pressure of water in a given space compared with the vapour pressure at saturation for the same dry bulb temperature.
Renewable energy: Any form of primary energy, for which the source is not depleted by use. Wind and solar are always renewable, biomass can be renewable if its consumption is matched by re-growth. Non-renewable energy refers to any form of primary energy, the supply of which is finite and hence its use depletes the existing stock. It generally refers to fossil fuels.
Softwood: Generally, one of the botanical groups of trees that, in most cases, have needlelike or scalelike leaves; the conifers; also, the wood produced by such trees. The term has no reference to the actual hardness of the wood.
Solar Collector: A system that absorbs solar radiation in order to heat a medium.
Sp. gr.: Specific gravity.
Storage.: Bulk or stickered piling of air- or kiln-dried wood products with protection from the weather in accordance with the desired level of moisture content; protection might be tarpaulins, or open, closed, or closed and heated sheds.
Sun shields.: In air drying, plywood panels, boards, or some other type of shield placed to protect the ends of piles from direct sun. The purpose is to retard end drying, thus minimize end-checking and end-splitting.
Temperature: May be defined as the condition of a body which determines the transfer of heat to or from other bodies; it is a measure of the thermal potential of a body.
Dry-bulb temperature: Temperature of air in a yard or drying apparatus indicated by any temperature-measuring device with its sensitive element or bulb uncovered.
Mean monthly temperature: In air drying, the average dry-bulb temperature over a period of a month. Usually obtained from Weather Service records.
Wet-bulb temperature: The temperature indicated by any temperature-measuring device the sensitive element of which is covered by a water-saturated cloth (wet-bulb wick).
Vapour barrier: In kiln drying, a material with a high resistance to vapour movement that is applied to dry kiln surfaces to prevent moisture migration.
Vent: In kiln drying, an opening in the kiln roof or wall that can be opened and closed to control the wet-bulb temperature within the kiln.
W (watts): SI unit of power. Symbol is W. Multiples like kilowatts (1 kW = 1000 W) or megawatts (1 MW =1000,000 W) are also used.
W.B.: Wet bulb
W.B.D.: Wet bulb depression

Wood: The tissues of the stem, branches, roots of a woody plant lying between the pith and cambium, serving for water conduction, mechanical strength, and food storage, and characterized by the presence of tracheas or vessels.
Wp (peak-watts): Unit of the capacity of PV modules. PV modules are rated by their peak power output. The peak power is the amount of power output a PV module produces at Standard Test Conditions (STC) defined as module operating temperature of 25 °C in full sunshine (irradiance) of 1000 W/m² This is a clear summer day with sun approximately overhead and the cells faced directly towards the sun. Multiples: peak-kilowatts (1 kWp=1000 Wp), peak Megawatts (1 MWp=10^6 Wp)
Wt.: Weight

References of the Appendix

[1] BUX, M., MÜHLBAUER, W., BAUER, K., KÖHLER, B.: Solar crop drying in developing countries, Berne, (2002).
[2] ITDG: Cocoa and Chocolate, http://itdg.org, Technical Brief
[3] EKECHUKWU, O.V.: Experimental studies of integral-type natural-circulation solar-energy tropical crop dryers, Ph.D. (1987).
[4] BRENNDORFER, B., KENNEDY, L., BATEMAN, C.O.O., MREMA, G.C., WEREKO-BROBBY, C.: Solar dryers- their role in post harvest processing., London, (1985).
[5] INTERNATIONAL-LABOUR-ORGANISATION: Solar drying: practical methods of food preservation, Geneva, (1986).
[6] VANDERHULST, P., LANSER, H., BERGMEYER, P., FOETH, F., ALBERS, R.: Solar Energy - Small scale applications in developing countries, Amsterdam, (1990).
[7] SHILTON, N.: Food Process Engineering - Drying, http://www.ucd.ie/food/html/homepage/newdrying.doc,
[8] DRAXLER, J.: Thermische Verfahrenstechnik, Skriptum zur Vorlesung pp (2002).
[9] PROCTOR, D.L.: Grain Storage Techniques, Rome, (1994).
[10] Technology, D.o.W.S.: Wood Anatomy Lab-Glossary, Kyungpook National University, http://bh.kyungpook.ac.kr/~sjpark/st3-2-9.htm, (n.y.).
[11] EKECHUKWU, O.V.a.N.B.: Review of solar-energy drying systems II: an overview of solar drying technology, Energy Conversion & Management 40 pp 615-655, Pergamon (1999).
[12] IEA, Solar Heating and Cooling Programme: Potential for Solar Drying in the World, October 1998

Internet Sources

Expert consultation on planning the development of sundrying techniques in Africa
http://www.fao.org/inpho/vlibrary/x0018e/X0018E00.htm

Grain storage techniques
http://www.fao.org/docrep/t1838e/T1838E00.htm

Fruit and vegetable processing
http://www.fao.org/docrep/V5030E/V5030E00.htm

Compendium on Post-harvest Operations
http://www.fao.org/inpho/compend/toc_main.htm

The United Nations University Press, *Food and Nutrition Bulletin,* Volume 7, Number 1, March 1985
http://www.unu.edu/unupress/food/8F071e/8F071E00.htm