SOLAR DRYERS: A STATE-OF-THE-ART REVIEW

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Abstract. *A considerable amount of the expressiveagricultural production of Brazil is lost on inappropriate drying and storage processes. Great part of the basic food products is produced by small producers, which, in general, don't have the appropriate equipments for drying and storing, using natural sun to dry. Most part of the big agricultural producers, and a few small ones, organized in co-operative societies, use high temperature drying systems. These systems offer increase of quality of the dried products, but demand higher costs. Solar dryers are an alternative for the small producers, since they involve low costs and operate through a renewable and non-pollutant energy source. This paper is a review of the most used solar dryers, describing the available techniques and the main advantages and disadvantages of these devices.*

Keywords. *Solar Chimney, Solar Drying of Bananas*

1. Introduction

An analysis of the agricultural situation of the world reveals the great disparity between the developed and the developing countries. In the developed countries, the harvest, drying and storage processes are usually mechanised. In the developing countries, however, a large part of the food production is processed without the adequate harvest systems and the products are directly exposed to the sun.

In the developed countries, the grain, fruit and vegetables harvest is done by modern equipments, requiring an immediate and quality pos processing (drought and storage). Therefore, the sun drying was replaced by the high-temperature drying (the difference between the drying temperature and the ambient air temperature is over 10ºC), which requires a high energy consumption to heat the drying air, to set it in motion and to revolve the product (when this process is automatic). Although, according to Mühlbauer et. al (1996), the 1973 world energy crisis lead to the partial replacement of the continuous high-temperature dryers by discontinuous low-temperature dryers (in which the difference between the drying temperature and the ambient air temperature is under 10ºC). In spite of demanding a longer time to perform the drying, the low-temperature drying presents better homogeneity, lower energy consumption and final products with better quality (colour, texture, taste and lower fissure incidence).

In developing countries, like Brazil, many producers' lack of appropriate systems for drying and storing grains and fruits, which results in high losses and reduction of the food availability. Mühlbauer et al. (1996) believe that, in a near future, the food production in many of these countries will not be enough to supply the needs of the increasing populations. In these countries, the sun drying is the most used drying method. The drying product is arranged in thin layers over trays, boards or pavement, being exposed it to the wind and to the solar radiation. The open-air sun drying, in spite of requiring lower investments, presents high crop losses ensue from inadequate drying, fungal attacks, insects, birds and rodents encroachment, unexpected down pour of rain and other weathering effects.

In order to assure a continuous food supplying to the growing world population and to make it possible for the farmers to increase the quality and profitability of their production and reduce their losses, it is necessary to develop drying methods with high efficiency and low costs. The high-temperature dryers used in the developed countries are economically viable only when used in large plantations. Therefore, the current world energy crisis and the inconstancy of the prices of petrol in the international market require a strategic energy technology. In order to overcome the problems that exist in the countries in development, the use of solar dryers are a promising alternative. Researches show that agricultural products can be dried in a satisfactory way using solar energy or other energy alternative sources (Ivanova and Andonov, 2001).

This paper presents a study of the operation of the most important solar dryers developed in the last years, of the new technical details proposed and of the most suitable use for each device. The analysed devices are presented according to the modern classification for dryers proposed by Ekechukwu and Norton (1999).

2. Solar Dryers

According to Ekechukwu and Norton (1999), the solar dryers must be classified according to their operating temperatures and according to their heating modes and the manner in which the solar heat is utilised. In the **passive** dryers, the drying flow occurs by natural convection, while in the **active** dryers the airflow is generated by forced convection, using, generally, a second energy source.

Moreover, the solar dryers can also be classified according to the exposure of the product to the solar radiation and to the structure of the device. In the **integral-type** dryers, the drying chamber is localized in the same structure of the absorbent surface (which heats the air used to dry). Thus, solar radiation impinges directly on the drying products. In the **distributed-type** dryers, the drying chamber is an independent structure and the product doesn't receive direct incidence of solar radiation. The **mixed-mode** dryers combine the features of the integral-type and the distributed-type solar dryers. The combined action of solar radiation incident directly on the drying product and pre-heated in a solar air heater furnishes the heat required for the drying process.

2.1. Integral-Type Passive Solar Dryers

Basically, three types of integral-type passive solar dryers can be identified: there are several configurations that would fit this class of dryers. Basically, there are three configurations: cabinet-type dryer, collector with chimney dryer, and greenhouse with chimney dryer.

The ***natural convection cabinet-type solar dryer*** consists of an opaque box, with the inner surfaces (base and lateral walls) operating as solar radiation absorbers. A translucent tilted (according to the local latitude) cover is placed over the dryer frame. The holes on the base allow the airflow inlet and the upper holes allow the outlet of the hot air. This dryer can be coated with an insulation material, in order to reduce the thermal losses to the environment. The drying product is usually arranged over trays placed above the absorbent base of the dryer. Sharma et. al (1995) present a cabinet-type solar dryer built in wood, with a glass cover and absorbent surfaces painted in black (Fig. 1a), very well suited to dry small quantities of fruits and vegetables on the domestic or household scale.

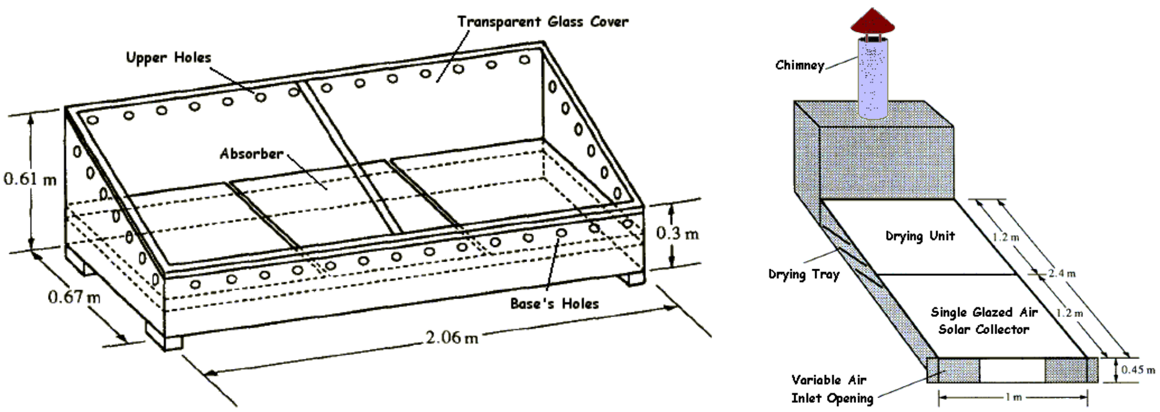

Figure 1- Cabinet-type dryer (a) and Collector with chimney dryer (b) (Adaptation of Sharma et. al (1995))

The ***Collector with Chimney Solar Dryer*** consists of a flat air solar collector connected to a chimney. The air solar collector is a rectangular tilted box, with an inner absorbent surface, covered by a translucent material. The first part of the solar collector is used to heat the flow (by convection), and the second part is used as a drying tunnel, installing drying trays to place the drying products. The slope of the collector, allied to the suction phenomenon performed by the chimney, provides the development of a natural convection airflow. Sharma et. al (1995) present a dryer that operates with this principle (Fig. 1b), developed in Italy to dry limited quantities of agricultural products in farms.

The ***greenhouse with chimney solar dryer*** consists of a translucent greenhouse attached to a chimney. The solar radiation transmitted by the cover of the greenhouse heats the ground and, consequently, the air used for drying. The natural convection airflow produced passes through the product (that receives direct solar radiation), is suctioned by the chimney, and leaves the device. These dryers present low construction and operation costs, simple technology and a high mass flow. Ferreira et. al (2000) propose the use of the solar chimney, device conceived by Schlaich (1995) to produce electrical energy, as a greenhouse with chimney radial solar dryer. Ekechukwu and Norton (1999) developed a longitudinal solar dryer, schematized in Fig. (2).

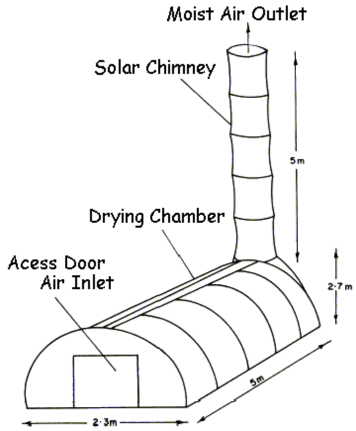

Figure 2 – Greenhouse and Chimney Solar Dryer (Adaptation of Ekechukwu and Norton (1999))

2.2. Distributed-type Passive Solar Dryers

The distributed-type passive solar dryers consist of a solar flat plate air collector connected to an opaque drying cabinet. Ambient temperature air is admitted at the entrance of the air solar collector, passing between the absorbent plate and the translucent cover. During the day, the absorbent plate absorbs the solar radiation and heates the airflow by convection. The hot airflow enters the drying chamber by natural convection, passing upward through the drying tray and removing a portion of the humidity of the products. The flow is suctioned by the chimney and leaves the device.

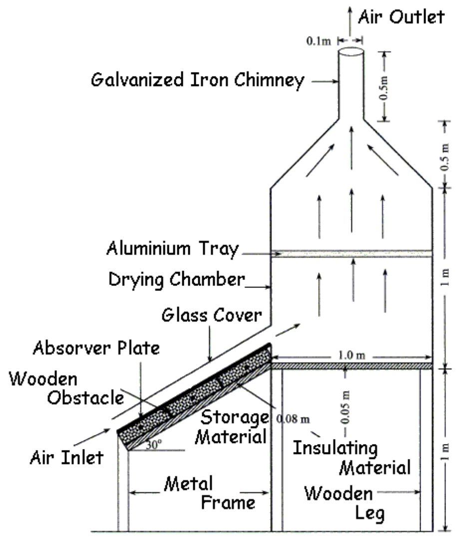

Figure 3 – Distributed-type passive dryer (Adaptation of El-Sebaii et. al (2002))

El-Sebaii et. al (2002) constructed a distributed-type passive solar dryer at Egypt (Fig. 3). They used sand under the collector plate, as a heat storage material. The use of a storage material allowed the continuous operation of the device, removing humidity from the products even at night. The air temperature at the inlet of the drying chamber varied from 45,4ºC to 55,5ºC, a zone suitable to dry most of the agricultural products. The dryer was able of drying 10 kg of grapes (or peas) in 20 hours of sun exposure.

Pangavhane et. al (2002) proposed a solar dryer similar to the dryer built by El-Sebaii et. al (2002) to dry fruits and vegetables in India (Fig. 4). The solar collector is constituted by U-shape corrugations operating as fins, increasing the heat transferred to the air. The drying chamber is coated with glass wool insulation, reducing the heat losses to the environment. Grapes were dried in the device, in a shorter period of time compared to the traditional drying, producing better quality raisins.

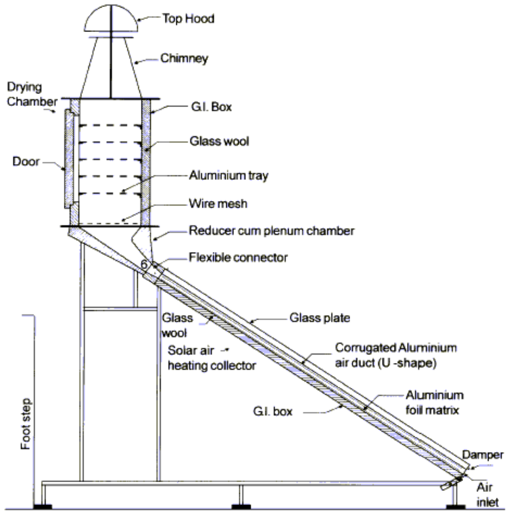

Figure 4 – Distributed-type passive dryer (Adaptation of Pangavhane et. al (2002))

2.3. Mixed-mode Passive Solar Dryers

The mixed-mode passive solar dryers, as well as the distributed-type passive dryers, consist of an air solar collector joint to a drying chamber. Nevertheless, the drying chamber of the mixed-type dryers has a translucent cover, allowing the product to receive direct incidence of the solar radiation.

Simate (2003) describes a dryer that consists of an air solar collector with a drying chamber covered by glass. The slope of the solar collector being was chosen in order to benefit the natural convection flow. A mixed-mode and an indirect-mode natural convection solar dryers (with the same basic configuration) for maize have been optimized and their performance compared. The time required for the drying on the mixed-mode type was shorter and the moisture content distribution of the dried grain was more uniform.

Basunia and Abe (2001) present a mixed-mode passive solar dryer to dry grains (Fig. 5). A 12 cm diameter chimney at the top of the cover provides a significant increase of the mass flow of the drying air. Thin-layer solar-drying experiments were conducted with medium grain rough rice. The dryer, with a solar total collector area of 2,6 m^2, presented natural convection velocities varying from 0,2 m/s to 1,4 m/s, and a maximum increase on the temperature of the drying air of 15ºC, comparing to the external environment temperature.

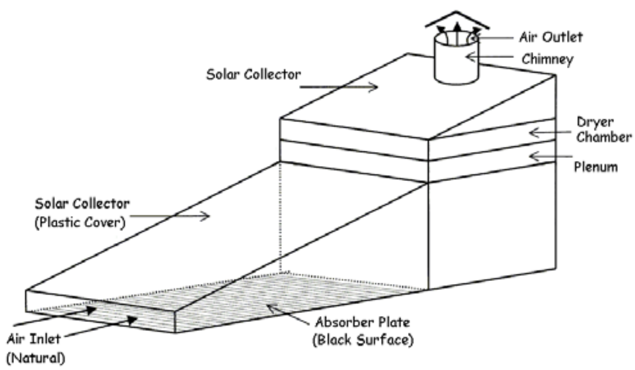

Figure 5 – Basunia and Abe’s Solar Dryer (2001) (Adaptation of Basunia and Abe (2001))

Ekechukwu and Norton (1999) present a solar and wind-ventilated mixed-mode dryer (Fig. 6). The dryer retains the main features of a mixed-mode natural-circulation solar-energy dryer, the distinctive feature being its air circulation system. Air is drawn through the dryer by wind-powered rotary vanes located on top of the dryer chimney, which increase the mass flow without raising the operational costs of the device. Additional heating is obtained from direct absorption of solar radiation through transparent walls of the drying chamber.

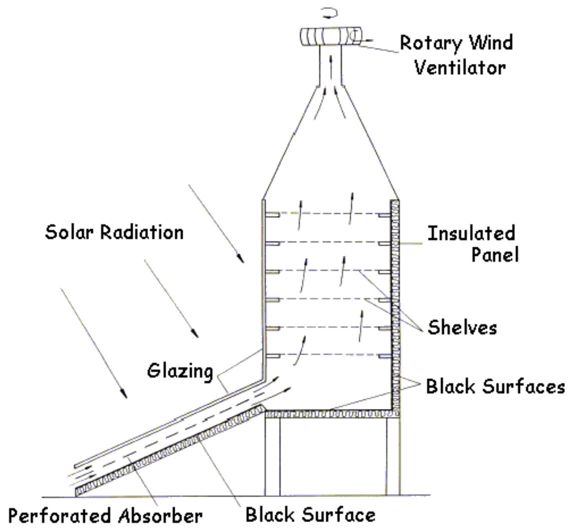

Figure 6 – Solar and wind-ventilated mixed-mode dryer (Adaptation of Ekechukwu and Norton (1999))

2.4. Integral-type Active Solar Dryers

The most known integral-type active solar dryers are the solar tunnel dryers. In these devices, the airflow is forced to inlet the dryer by fans. A flat-plate collector absorbs a portion of the incident solar radiation and heates the airflow in the tunnel. After leaving the collector, the airflow passes through the products in the drying tunnel and leaves the device.

Figure (7) shows a solar tunnel dryer developed by Schirmer et al. (1996) in Thailand. In this dryer, the flow is generated by three small axial fans drove by a photovoltaic panel. In experimental tests conducted, 300 kg of bananas were dried in 3,5 days on the dryer. To the same climatic conditions, the traditional sun drying required a 4,5 days period. During the experimental tests, the temperature of the drying air of the solar tunnel varied between 40ºC and 65ºC.

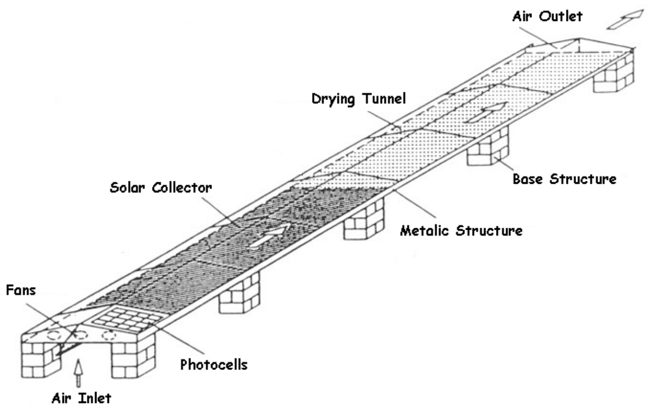

Figure 7 – Tunnel Dryer (Adaptation of Schirmer et al. (1996))

Bala et. al (2003) performed drying experiments with pineapples using a tunnel solar dryer, in Bangladesh. The flow was generated by two fans drove by a photovoltaic panel. The tunnel is 20 m long and 2 m large. The first half of the tunnel constitutes the collecting area and the second half, the drying area. The insulating material was glass wool. The dryer was able to dry 150 kg of pineapples in 20 hours, presenting good quality products (free of contamination by dust, insects or micro organisms).

Mahmutoglu et al. (1996) present an integral-type active solar dryer to dry sultana grapes (Fig. 8). The velocity of the forced flow in the dryer was 3 m/s. The maximum temperature of the drying air was 50ºC, for air ambient temperatures varying from 17ºC to 40ºC.

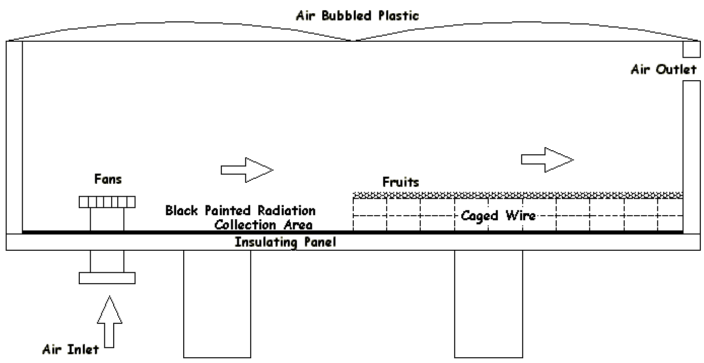

Figure 8 – Dryer conceived by Mahmutoglu et al. (1996) (Adaptation of Mahmutoglu et al. (1996))

2.5. Distributed-type Active Solar Dryers

There are several configurations for distributed-type active solar dryers described in the literature. Muller et. al. (1989) performed a study about dryers for herbs and medical plants similar to solar greenhouses (Fig. 9). Experimental runs pointed out drying air temperatures of 60ºC, at most. In these dryers, the drying product was not expose directly to the sun, in order to avoid the degradation of the chlorophyll and consequent lost of the colour.

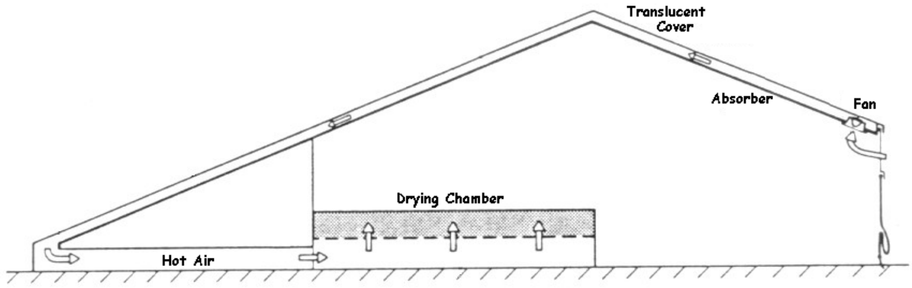

Figure 9 – Dryer conceived by Muller et al. (1989) (Adaptation of Muller et al. (1989))

Sharma et. al (1995) present a distributed-type active solar dryer constituted by a solar flat plate collector with a drying chamber (Fig. 10). The drying chamber has drying trays capable of supporting from 75 to 100 kg of drying fruits (industrial scale).

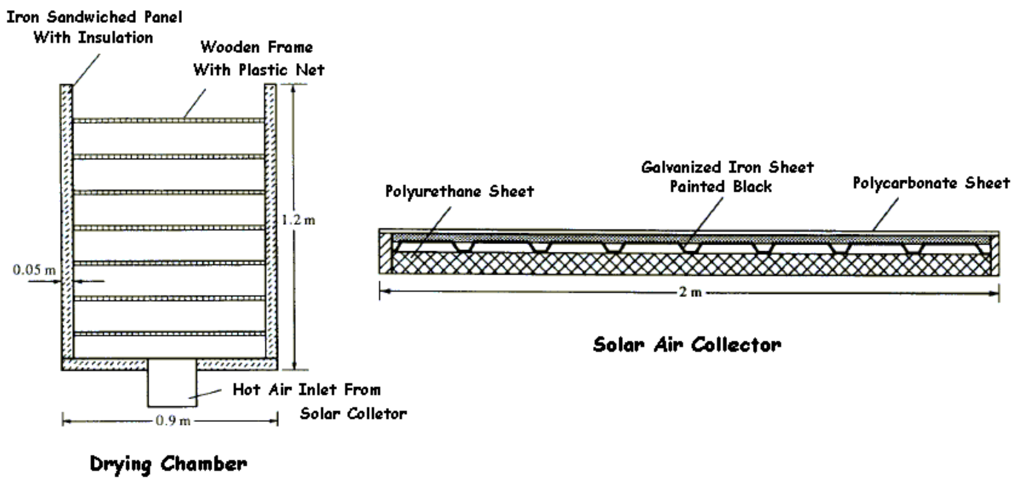

Figure 10 – General overview of the indirect-type multi-forced convection solar dryer (adaptation of Sharma et. al., 1995)

Togrul and Pehlivan (2002) present a dryer with conical concentrator collector (Fig. 11) developed for solar thin layers drying of apricots in Turkey. The solar dryer used consists of a a solar air heater with conical concentrator and a drying cabinet, operating in forced convection. The solar air heater is able to rotate via two satellite antenna motors (drove by photovoltaic cells) to face the conical concentrator continuously towards the sun.capacity.

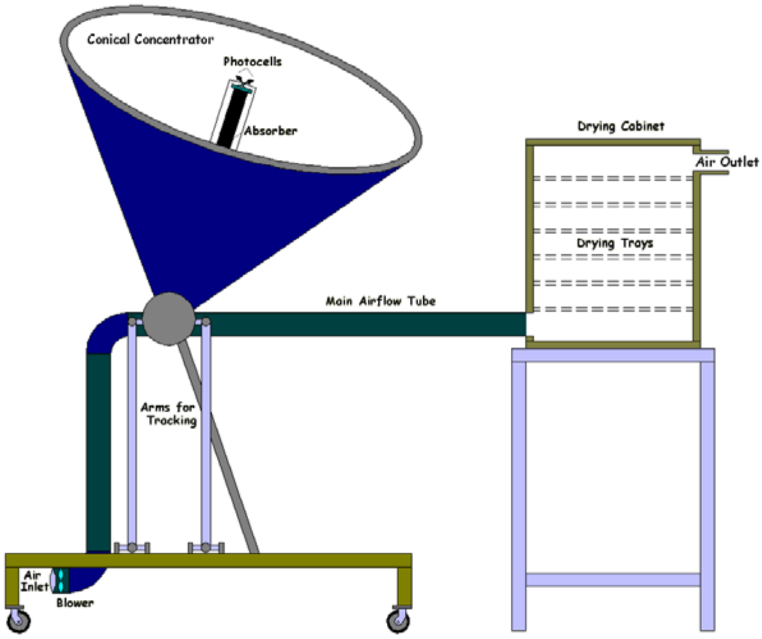

Figure 11 – Dryer conceived by Togrul and Pehlivan (2002)

2.6. Mixed-mode Active Solar Dryers

Condorí et. al (2001) and Condorí and Saravia (2003) describe a tunnel-greenhouse solar dryer (Fig. 12). Air ambient temperature air is admitted at the collect area and is directly heated by the solar radiation. The hot airflow is moved from the greenhouse into the tunnel by an electrical fan. A line of carts with several trays containing the product are moved manually inside da tunnel. A semi-cylindrical translucent plastic cover is placed over the greenhouse cover in order to reduce the heat losses (by convection to the environment) of the hot and humid flow leaving the drying tunnel and to reuse part of the heat that would have been released.

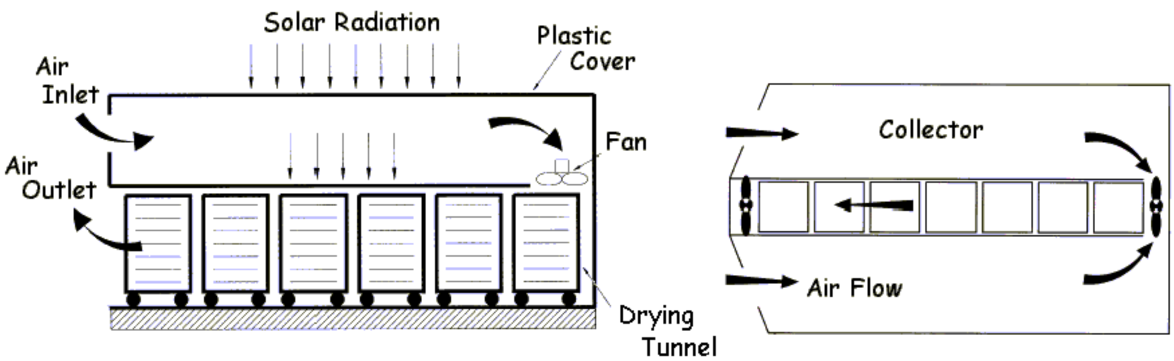

Figure 12 – Dryer conceived by Condorí et. al (2001) (Adaptation of Condorí et. al (2001))

3. Hybrid-type Solar Dryers

In the hybrid-type solar dryers, a source of energy is used to complement the solar energy during low incidence of solar radiation periods, maintaining the drying process continuous and improving the system control capacity of the drying parameters.

Bena and Fuller (2002) present a direct-type natural convection solar dryer with an auxiliary air heating system that operates by a simple biomass burner (Fig. 13). The capacity of this dryer was of 20 to 22 kg of fruits. The dryer presented a better product quality regarding to the products dried in an exclusively solar system.

Besides, this dryer has lower operational costs compared to a conventional dryer (air heating performed using electrical energy or burnt of fossil fuel).

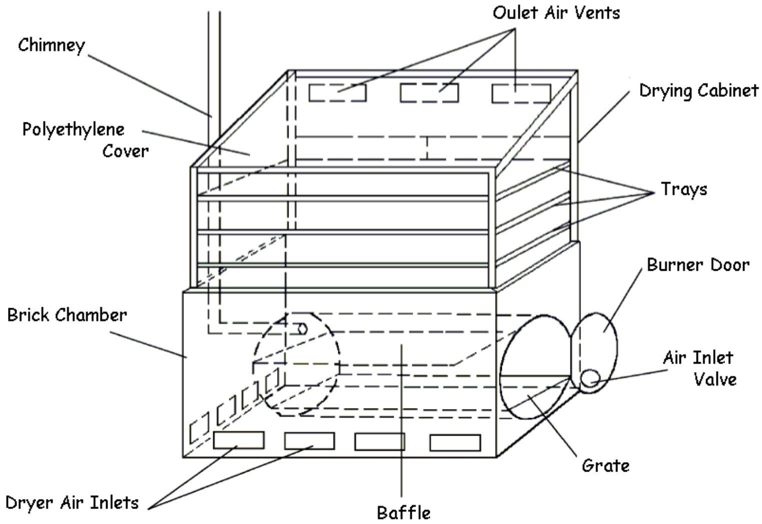

Figure 13 – Dryer conceived by Bena and Fuller (2002) (Adaptation of Bena e Fuller (2002))

Ivanova et. al (2003) present a fruits and vegetables dryer that uses solar energy and heat of geothermal water from a natural field to heat the drying air (Fig. 14), using the solar availability and the existence of many natural hot water sources in Bulgaria.

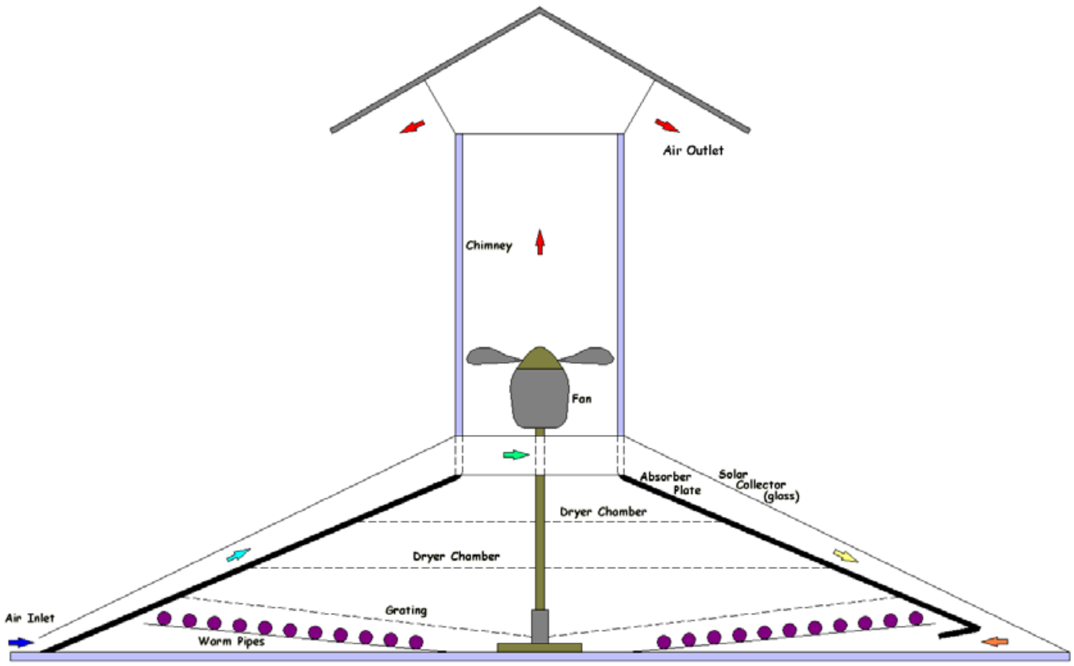

Figure 14 – Dryer conceived by Ivanova et. al (2003)

4. Technical Analysis

The major problem of the solar dryers is the variation of the drying flow parameters caused by the daily variations of the incident solar radiation. In order to complement the incident solar radiation and to control the drying parameters, auxiliary energy sources can be used. Bena and Fuller (2002) used a biomass back-up heater. Ivanova et. al. (2003) adopted a fan to generate the airflow and tubes heated by geothermal sources to reduce the oscillations of the temperature of the drying air. The use of auxiliary energy sources provides a solar drying with similar quality to the one performed by artificial dryers, with lower operational costs and low damage to the environment.

It was observed that the drying air in some passive solar dryers (cabinet-type dryer described by Sharma et. al. (1995), and tilted collector dryer used by Simate (2003)) usually presents low velocities. This problem can be reduced using chimneys at the outlet of the device, as used in the collector with chimney dryer conceived by Sharma et. al. (1995), in the greenhouse with chimney dryer of Ekechukwu and Norton (1999) and in the distributed-type dryer of Pangavhane et. al. (2002). Since the chimneys promote a suction of the air in the dryer, they are able to increase the mass flow of the drying air. Another option would be the use of fans (converting the passive dryer in an active dryer) that increase and stabilize the mass flow, although it results in higher drying costs.

The use of higher chimneys provides the production of higher drying mass flow. Although, the increase of the flow velocity reduce the temperature of the absorbent surface faster, reducing the temperature of the air. One of the most noticed disadvantages of the passive solar dryers is the lack of control of the drying flow parameters. This problem can be solved using a flow-rate control mechanism, which allows, indirectly, the adjustment of the temperature of the flow. Sharma et. al. (1995) used a variable air inlet opening on the collector dryer, which allowed, in a cheap and simple way, the control of the mass flow entering the device. Other mechanisms can be used with the same objective, for example, a valve in a cross section of the chimney. These mechanisms can reduce the time required for drying a product by promoting an increase of the mass flow at the begining of the drying period (when the superficial humidity of the product and the humidity remotion ratio by the air are high) and higher temperatures at the end of the process (when the superficial humidity of the product is low and, therefore, a low relative humidity flow is necessary).

A problem detected in most of the analysed solar dryers is the insufficient heating of the drying air during low incidence of solar radiation periods, and the airflow stagnation in passive dryers at the same periods. The use of storage materials under the absorbent surface allows that the heat stored during the incidence of solar radiation period is transferred to the flow during the night, guaranteeing the continuous operation of the dryers. The storage materials were used in the distributed-type passive dryer proposed by El-Sebaii et. al. (2002) and in the greenhouse with chimney dryer presented by Ekechukwu and Norton (1999).

It is observed, therefore, that the passive solar dryers that use a chimney to increase the mass flow, energy absorbent materials to assure the continuous operation of the dryer (even during low incidence of solar radiation periods) and flow-rate control mechanisms present conceptive details that provides, in a simple and cheap way, improve the drying capacity of this type of dryer.

5. Conclusions

A review of the recently developed solar dryers, including their constructive details and operational techniques, was presented in this paper. These dryers were classified regarding their operational principles and structural frames, according to the modern classification proposed by Ekechukwu and Norton (1999).

A technical analysis of the solar dryers was done, listing their main problems and proposing simple conceptive solutions used in recently developed solar dryers.

The solar dryers are an interesting and viable alternative for the agricultural products drying, since they operate with a free, renewable and non-pollutant energy source.

6. References

Bala, B. K.; Mondol, M. R. A.; Biswas, B. K.; Das Chowdury, B. L.; Janjai, S., 2003, “Solar Drying of Pineapple Using Solar Tunnel Drier”, Renewable Energy, Vol. 28, No. 6, pp. 183-190.

Basunia, M. A. and Abe, T., 2001, “Thin-layer Solar Drying Characteristics of Rough Rice Under Natural Convection”, Journal of Food Engineering, Vol. 47, pp. 295-301.

Bena, B. and Fuller, R. J., 2002, “Natural Convection Solar Dryer With Biomass Back-up Heater”, Solar Energy, Vol. 72, No. 1, pp. 75-83.

Condorí, M., Echazú, R. and Saravia, L., 2001, “Solar Drying of Sweet Pepper and Garlic using the Tunnel Greenhouse Drier”, Renewable Energy, Vol. 22, pp. 447-460.

Condorí, M. Saravia, L., 2003, “Analytical Model for the Performance of the Tunnel-Type Greenhouse Drier”, Renewable Energy, vol. 28, pp. 467-485.

Ekechukwu, O. V. and Norton, B.,1999, “Review of Solar-energy Drying Systems II: an Overview of Solar Drying Technology”, Energy Conversion and Management, Vol. 40, pp. 615-655.

El-Sebaii, A.A., Aboul-Enein, S., Ramadan, M. R. I., El-Gohary, H. G., 2002, “Experimental Investigation of an Indirect Type Natural Convection Solar Dryer”, Energy Conversion and Management, Vol. 43, pp. 2251-2266.

Ferreira, A. G., Cortez, M. F. B., Valle, R. M. and Brasil, C. S., 2000, “Estudo Numérico do Escoamento de ar em Convecção Mista no Interior de um Dispositivo Radial de Secagem”, Proceedings of CILAMCE 2000.

Ivanova, D. and Andonov, K., 2001, “Analytical and Experimental Study of Combined Fruit and Vegetable Dryer”, Energy Conversion Management, Vol. 42, pp. 975-983.

Ivanova, D., Enimanev, K. and Andonov, K. 2003, “Energy and Economic Effectiveness of a Fruit and Vegetable Dryer”, Energy Conversion and Management, Vol. 44, pp. 763-769.

Mahmutoglu, T., Emír, F. and Saygi, B., 1996, “Sun/Solar Drying of Differently Treated Grapes and Storage Stability of Dried Grapes”, Journal of Food Engineering, Vol. 29, pp. 289-300.

Mühlbauer, W.; Müller, J.; Esper, A. e Bux, M., 1996, “Secagem Solar e ao Sol para Produtos Agrícolas e Florestais” (Tradução para o Português), Universidade de Hohenheim/Instituto para Engenharia Agrícola nos Países Tropicais e Subtropicais, Stuttgart/Alemanha, 55p.

Müller, J.; Reisinger, G.; Kisgeci, J.; Kotta, E. and Mühlbauer, W.;1989, “Development of a Greenhouse-Type Solar Dryer for Medicinal Plants and Herbs”, Solar and Wind Tecnology 6, Vol. 5, pp. 523-530.

Pangavhane, D. R., Sawhney, R. L. and Sarsavadia, P. N.,2002, “Design, Development and Performance Testing of a New Natural Convection Solar Dryer”, Energy, Vol. 27, pp. 579-590.

Schlaich, J., 1995, “The Solar Chimney, Electricity from the Sun”, Edition Axel Menges, Stuttgart, Alemanha, 59p.

Schirmer, P.; Janjai, S.; Esper, A.; Smitabhindu, R. and Mühlbauer, W., 1996, “Experimental Investigation of the Performance of the Solar Tunnel Dryer for Drying Bananas”, Renewable Energy, Vol. 7, no 2, pp. 119-129.

Sharma, V. K.; Colangelo, A. and Spagna, G., 1995, “Experimental Investigation of Different Solar Dryers Suitable for Fruit and Vegetable Drying”, Renewable Energy, Vol. 6, no 4, pp. 413-424.

Silva, J., 2000, “Secagem e Armazenagem de Produtos Agrícolas”, Editora Aprenda Fácil, 1a Edição, Viçosa, Brasil, 502p.

Simate, I. N., 2003, “Optimization of Mixed-mode and Indirect-mode NaturalConvection Solar Dryers”, Renewable Energy, Vol. 28, pp. 435-453.

Togrul, I. T. and Pehlivan, D., 2002, “Mathematical Modelling of Solar Drying of Apricots in Thin Layers”, Journal of Food Engineering, Vol. 55, pp. 209-216.