Application of sustainable renewable energy in developing countries: Food Drying and Solar Cookers usage in Northern Argentina

Víctor José Passamai[1] and Jorge Luis Alvarado[2]

[1]Departamento de Física, Facultad de Ciencias Exactas, Universidad Nacional de Salta, Avda. Bolivia 5150 – 4400 Argentina (passamai@unsa.edu.ar)/[2]Department of Engineering Technology and Industrial Distribution, Texas A&M University, Texas, 3367 TAMU College Station, TX, USA (alvarado@entc.tamu.edu)

Abstract

The National University of Salta (UNS), at the City of Salta in northern Argentina, was one of the first academic institutions to start research in the area of solar energy applications in the country. In 1982, a Non Conventional Energy Research Institute (INENCO) was founded in UNS to sponsor a variety of solar energy related projects. Since then, solar drying and cooking have been two of the most important research contributions UNS has made in the field of renewable energy. INENCO first contributions include research projects in the area of computer modeling of solar-driven processes, and the development, design and construction of prototypes and devices that utilize solar energy. Specifically, solar dryers and cookers have been built and successfully tested in recent years. Coincidentally, due to economic uncertainties and difficulties experienced by the country in the last few years, INENCO has consciously decided to disseminate practical know-how and provide training in the area of solar drying and cooking in a concerted effort to help the population to become more self-reliant. A program has been set up to provide appropriate technical education to maximize the use of abundant resources like the earth and sun.

In this paper, a detailed description of the efforts undertaken by INENCO and UNS is presented. The paper focuses on recent successful initiatives, valuable research activities, and lessons learned. Specifically, a detailed presentation of successes and challenges in the application of solar-driven technology from the Argentinean point of view is presented. Findings and observations are summarized and shared to foster better cooperation with other nations within the region and countries interested in the development and implementation of solar drying and cooking. This should encourage discussion among participants on how to support research activities and implementation projects from within and outside the region that can mutually benefit a wide range of stakeholders.

Introduction

The Argentine Solar Energy Association (Asociación Argentina de Energía Solar, ASADES), founded in June 1974 by a group of solar energy researchers from Buenos Aires has been quite active in the research and development of solar energy and its applications. The association's main objectives include scientific research and technological application of solar energy throughout the country, specifically where solar energy is abundant and makes economic sense. ASADES has also served as an integrating forum, where all the new members and researchers can exchange information on a variety of topics including teaching, research, development and application of solar energy at the national level.

The ASADES Statute established the need to direct solar energy research towards solving Argentinean energy problems, coordinating joint programs between the different groups which include annual meetings of their members. The Solar Energy Group (SEG) at UNS which is an active member of ASADES began research activities as early as 1975 in Salta. One of the main objectives of the SEG at UNS is to study and develop solar drying and cooking techniques and prototypes. The following sections describe recent developments undertaken by SEG in the area of solar drying and cooking.

Solar drying and cooking

Solar drying and cooking are interrelated activities which have been studied for several years. In developing countries where access to power grids or reliable sources of energy is cumbersome and sometimes difficult, solar energy has proven time and time again to satisfactorily meet the energy needs of communities around the world. However, successful use of solar energy should always be accompanied by scientific and technical analysis of each application. In recent years, computer modeling of solar energy and its applications has taken a critical role in the development and design of prototypes. SEG has been active in the computer modeling of solar drying processes for a variety of vegetables. Collaboration with other universities has also been the driving force behind many of the successful applications of solar energy in Argentina. The University of Salta collaborated with the Ruhr Universität Bochum from Germany on a common research project involving solar drying possibilities of tobacco back in 1980. Also, the Bundes Ministerium für Forschung und Technologie (National Ministry for Research and Technology of Germany) invited Passamai (Co-Author) who developed a laboratory-scale tobacco dryer in 1981 which simulated solar drying. As a result, a paper was published in Germany in 1984 (Passamai et al., 1984). Following this same line of work, drying of red pepper was also modeled and another couple of international papers were published (Passamai, 1987). The main idea behind these different activities was the use of solar energy for vegetable drying where special emphasis was given to the water evaporation process, in which an internal *resistance* related to the water content in the material was found to be responsible for the delay in water loss. To facilitate the implementation of solar energy drying technology, a macroscopic approach was followed instead of studying all the complex microscopic processes involved in the drying of vegetables. A series of macroscopic experiments were designed to find internal resistances and their reciprocals, *conductances*, of vegetables which allow the drying process to be modeled and used in practical applications.

Solar cooking was also adopted back in 1980 by SEG. In 1995, Tom Lawand from the Brace Research Institute in Canada visited Salta, he and his collaborators introduced the first box-type solar cookers. As a result INENCO and SEG built the first successful prototypes in Salta. The following section presents the solar drying formulation that was followed to design and analyze a real solar dryer.

Solar drying model

A solar drying process of foodstuff can be studied and analyzed by understanding the rate of water loss as a function of time, *t*, or the kinetic behavior of water loss. The rate of water loss can be expressed by $n(t)$ whose units are $kg/(m^2s)$. Based on previous studies (Passamai and Saravia, 1997), it has been determined that a limited number of physical variables can be used to describe and predict the drying process. The variables are shown in Table 1.

Table 1. Physical variables for drying process of foodstuff

Variable	Description
T	Temperature of surrounding air, °C
H	Relative humidity of surrounding air
v	Velocity of surrounding air, m/sec
I	Incident solar radiation, W/m^2
X	Water content of product being dried

An equation of state for the drying process can be expressed as follows:

$$n = n(X, T, H, v, I) \quad (1)$$

As seen in equation 1, *X* is the only internal variable that can be associated to a particular product. The other variables are external since they are related to the surrounding air and the energy source. A schematic representation of the drying process can be seen in Figure 1.

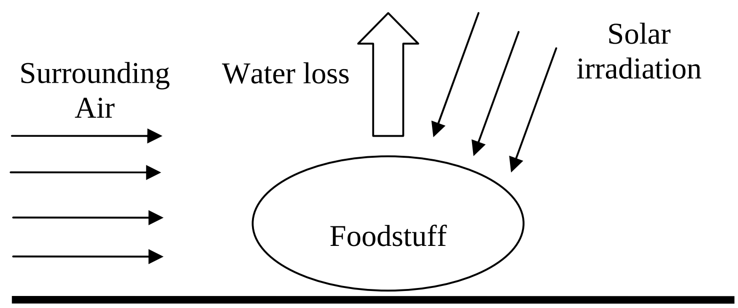

Figure 1. Schematic representation of solar drying process

The derivative of *X* with respect to time is related to *n* by its definition, given by:

$$n = -\frac{m_s}{A}\frac{dX}{dt} \quad (2)$$

where *A* and m_s are the exposed area and dry mass of the product under consideration, respectively. The action of the external variables *T*, *H*, *v* and the irradiation *I* can be stated as follows for the drying process of red peppers (Passamai and Saravia, 1997):

$$n = c_p(X)P_S(T)(1-H)v^{0.5} + c_i(X)v^{0.2}I \quad (3)$$

The definitions of all the variables can be found at the end of the paper.

Equation 3 can be generalized for any foodstuff or any other product to be dried as long as the product-dependent constants are determined experimentally. For instance, $c_p(X)$, $c_i(X)$ and the exponents of *v* are to be determined experimentally. The equation can be solved by using appropriate boundary (initial) conditions.

It is important to derive and formulate mathematical models like equation 3 so the drying process can be predicted and optimized. For instance, equation 3 shows how external variables affect the rate of evaporation. Therefore, it is essential to correlate external variables with the final goal, which is an improved solar drying process when designing and developing solar drying equipment and processes.

Solar cooker model

Solar cookers development continues to be a topic of interest in many parts of the world. Use of solar cookers represents a sustainable way of cooking with negligible negative effects. Solar cookers are an alternative to stoves that rely heavily on coal and wood. Design and development of solar cookers should rely on sound analytical tools so their use can be sustained in the future. For instance, a box-type solar cooker should and can be relatively easily modeled. Figure 2 shows the energy flows involved in the analysis and design of a box-type solar cooker. Figure 2 shows an empty box-type solar cooker that receives constant solar irradiation on its transparent cover.

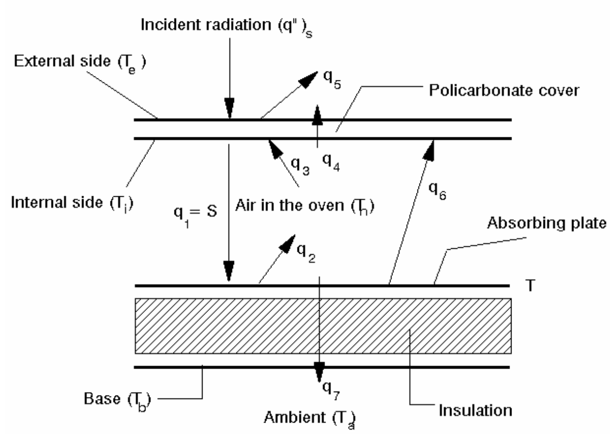

Figure 2: Schematic representation of energy flows in a box-type solar cooker

In formulating an appropriate model for a box-type solar cooker, one should neglect the cover's inclination. A box-type solar cooker can be considered as a plane solar collector operating under stationary conditions. The incident density of solar irradiation is given by q''_S (W/m^2). S is the fraction of energy absorbed by the collector plate. The initial temperature of the whole system is T_a (equal to the ambient) and as soon as it receives the solar radiation, the plate increases its temperature up to $T(t)$ as time progresses. Previous research indicates (Passamai, 1998) that the transparent polycarbonate cover internal side evolves to a temperature T_i, which is greater than the temperature of the external side, T_e.

The following assumptions are frequently used when analyzing box-type solar cookers:

- The mass of the collecting plate is evenly distributed on a plane, so that $f\sigma$ is the mass per unit effective area for an one-dimensional approximation (f is a correction factor to be determined that affects the actual mass density of the collecting plate)
- The plate temperature $T(t)$ is uniform throughout the plate's thickness
- The transparent polycarbonate cover has a non uniform temperature along its thickness (Passamai, 1998)

- The transparent cover absorbs heat from the plate exclusively (the difference between q''_S and S is due to reflection)

- The thermal inertia of the transparent cover is neglected, so that a linear thermal profile is assumed along the cover's thickness

- The air mass in the oven is neglected and only acts as a media for the convective heat transport

- The insulation of the base looses heat through conduction

- The ambient temperature is constant

- Heat losses through the base are the smallest of the system

To fully analyze the thermal performance of a box-type solar cooker, the following heat balance equations are introduced based on the assumptions and figure depicted above:

1. Absorbing plate:

$$S = f\sigma c\frac{dT}{dt} + U_p(T - T_i) + h_1(T - T_h) + \frac{k_b}{d_b}(T - T_b) \tag{4}$$

2. Air in the solar oven:

$$h_1(T - T_h) = h_2(T_h - T_i) \tag{5}$$

3. Transparent cover, internal side:

$$U_p(T - T_i) + h_2(T_h - T_i) = \frac{k}{d}(T_i - T_e) \tag{6}$$

4. Transparent cover, external side:

$$U_c(T_e - T_a) = \frac{k}{d}(T_i - T_e) \tag{7}$$

5. Base:

$$U_b(T_b - T_a) = \frac{k_b}{d_b}(T - T_b) \tag{8}$$

6. Global balance plate-air:

$$S = f\sigma c\frac{dT}{dt} + U(T - T_a) \tag{9}$$

Basically, equation (9) takes into account the heat capacity of the system.

The solution for the systems of equations shown above can be obtained by starting with (9), with the initial condition $T(0)=T_a$, which results in:

$$T = T_a + \frac{S}{U}(1 - e^{-\frac{U}{f\sigma c}t}) \tag{10}$$

Taking into account previous experimental data (Passamai, 1998), the following parameters can be adjusted to:

$$S=637\ W/m^2,\ U=9.5\ W/(m^2K),\ f=4.8,$$

These data are appropriate for a blackened iron plate with a *0.5 mm* thickness.

According to Duffie and Beckman (1991), the overall heat loss balance can be written:

$$U_c(T_e - T_a) = U(T - T_a) \tag{11}$$

Equation 10 was experimentally verified in the laboratory. T_e-T_a in equation (11) can be obtained by combining it with equation 7, resulting $T_i-T_e=dU/k(T-T_a)$. By taking equations 6 and 7 into account, and neglecting $h_2(T_h-T_i)$ in equation 6 (the oven and the internal side temperatures are almost equal) equation 10 can be expressed as:

$$T_e(t)=T_a+U/U_c[T(t)-T_a] \tag{12}$$

Similarly,

$$T_i(t)=T_e(t)+dU_c/k[T_e(t)-T_a] \tag{13}$$

Finally, from equation 5, the air temperature $T_h(t)$ of the oven can be obtained. The physical model just presented agrees well with experimental data, within a 2 % of discrepancy.

As in the case of solar drying, it is important to formulate macroscopic mathematical models so solar cooking can be predicted and optimized. The following section shows the outcomes of the previous analytical work which was used in the design, development and construction of solar cookers.

Development of designs and prototypes of solar cookers

The first solar cooker used in Salta was built by Ricardo Echazú in 1982, following the indications of Maria Telkes (Telkes, 1959). Echazú's prototype was made of iron which added considerable weight. Ricardo Echazú experiments helped Tom Lawand in the development of a more robust solar cooker in 1995. Consequently, Éric Brunet and Ricardo Caso from UNS built the first modern solar box-type cookers in 1995 but too heavy for mass production (over 15 kg). In 1996, Passamai was invited by Lawand to visit Brace Research Institute of Montreal, where lighter (5 kg) models of solar cookers were being built at the time. In 1997, Robert De Massy visited Salta and helped Passamai in the construction of a lighter solar cooker (3 kg). Figure 3 shows the three models developed during that time.

Figure 3: Box-type solar cookers of the Brace Research institute model.

All these box-type solar cookers used a polycarbonate cover in other to minimize weight while maximizing light transmission and durability, as the analytical models predicted.

The Salta model, the right one in figure 3, can be used as a solar dryer and cooker, because its cover can be easily removed to allow the flow of which carries away part of the product moisture. An even lighter and better insulated model was later developed in Salta, using polyurethane, glass wool and expanded polystyrene as insulating materials. Figure 4 shows the constructed prototype which weighs only 2.5 kg.

Figure 4: Lightest solar box-type cooker.

The prototype shown in Figure 4 costs around $150 (USD). A cheaper version ($3, USD) can be made of carton but it is not as long-lasting as one made of durable materials. Recent experiments (Passamai, 2002) showed that the thermal performance of the cheaper version is similar to that of a durable box-type solar cooker. The cheaper box-type solar cooker can be seen in Figure 5.

Figure 5: Low cost solar cooker

The low-cost solar cooker main attributes (Figure 5) are its high reflectivity, low cost (cheap) and ease of use. The materials can last several uses and can be easily replaced in case of rupture. The main disadvantage is that it can only be used by one person because of its small size. For a family of four, at least two units are required. On the other hand, their costs make it possible to purchase or make as many as necessary.

From the institutional point of view, INENCO has focused on the use of solar cookers with more expensive but better concentrators, Figure 6. Their main advantage is their size which allows to feed around 50 persons, ideally for schools in isolated places. Figure 6 shows this type of solar cookers, used in combination with box-type and insulated boxes.

Figure 6: Solar concentrators and box-type solar cookers with insulated boxes used to bake

Recent applications of solar cooking technology includes bread baking which works appropriately with solar concentrators when combined with insulated boxes (Franco et al., 2004).

Development of designs and prototypes of solar dryers

As in the case of solar cookers, solar dryers have also evolved in recent years thanks to lessons learned from the pasts. Solar drying has been used for centuries to dry foodstuff. The simplest solar drying technique consists in exposing the foodstuff to the sun, which avoids pollution. The first and most simple option to adopt in the field is to separate the drying product from the bare soil. Next, the product should be covered and protected from the surrounding air since it contains dust and other contaminants. Also, animals in the area should be avoided to protect the food from be eaten, spoiled or taken away. Examples of solar drying are shown in Figure 7.

Changing from large and inefficient extensions of land for sun-dried products to small commodities that can easily be managed by the producer is being considered in the province of Salta. Thanks to some recent initiatives of the local government, individuals and families are relying more and more on portable and greenhouse-type solar dryers. As a result, the products are better managed and protected against ambient conditions, animals, insects or even persons. Figure 8 shows examples of the latest type of solar dryers.

Figure 7: Evolution of solar drying in Argentina.

Figure 8: Two new models of solar dryers that protect sun-dried products

Comercial trends

Solar cookers and greenhouse dryers were developed by SEG at UNS with the intent of mass production, a breakthrough in the application of solar energy for cooking and drying. Since 2004, several solar cookers and dryers have been built and sold to private producers who are beginning to adopt this appropriate technology for their own benefit.

Around 50 solar cookers have been put in the hands of families in Santa Rosa de los Pastos Grandes, a community that receives a very convenient amount of solar irradiation all the year round which is located in the province of Salta. As for solar dryers, similar devices as the one shown on the right side of Figure 8 have been transferred to communities near Cachi, another town of the province. This has already produced a widespread and multiplicative effect among people who use these technologies since they readily want to adopt solar energy as a safe, ecological way to cook or dry foodstuff.

Conclusions

In this review, we have shown the latest developments of solar cooking and drying in northern Argentina. The approach used in the development of appropriate technology consisted in postulating analytical models for different processes involved in solar dryers and cookers. The design and construction of the prototypes were based on analytical models to ensure optimal performance. Field data indicates that the prototypes perform adequately. Attributes such as cost and durability should always be considered to ensure the widespread use of solar dryers and cookers.

Nomenclature

A area, m^2
$c_i(X)=(8.3X+3.8)\times 10^{-9}(s/m)^{2,2}$ variable coefficient (conductance) that modifies the radiation term in the radiation state equation
$c_p(X)=1,65\times 10^{-9}(X-1.3)(s/m)^{1,5}$ global conductance that modifies the pressure in the drying equation
H relative humidity of the air, %
I incident surface irradiation, W/m^2
m_s dry weight, kg
n surface density of water loss, $kg/(s\ m^2)$
P_s partial vapor pressure of the humid air, Pa
q_1 absorbing plate net incident radiation (equal to S) (W/m^2)
q_2 heat flux density between the plate and the air in the oven (free convection)
q_3 convective heat from the air to the internal side of the transparent cover
q_4 conduction heat flux through the cover
q_5 bulk heat loss from the cover to the ambient air
q_6 radiative exchange between the plate and the internal side of the cover
q_7 base heat loss through the thermal insulation (side effects neglected)
t time, s
T air temperature, K
v air velocity, m/s
X water content, bone dried basis, *kg of water* / *kg of bone dried mass*

References

Duffie J. A. and Beckman W. A. Solar Engineering of Thermal Processes, 2nd Edition, Wiley Interscience, New York, 1991, pp. 288-289.

Franco, J., Cadena, C. and Saravia, L.: “Multiple use communal solar cookers”. Solar Energy 77, pp. 217–223, 2004.

Passamai, V., Morhenne, J., Leiner, W. and Fiebig, M.: “Empirical mass transfer function for hot air drying of virginia tobacco” (Empirische StoffUbergangsfunktion fur die Heiβlufttrocknung von Virginia-Tabak). Chem. Eng. Tech., pp. 775-777, 1984.

Passamai, V.: “Laboratory and field experiments with a solar oven” (Experiencias de laboratorio y de campo con un horno solar). Avances en Energías Renovables y Medio Ambiente, Vol. 2, No. 1, pp. 02.29-02.32, 1998.

Passamai, V. and Passamai, M.: “Experiencias con cocinas solares tipo cookit de costo mínimo,” Avances en Energías Renovables y Medio Ambiente, Vol. 6, N° 2, pp. 10.33-10.36, 2002).

Passamai, V. and Saravia,L.: “Relationship between a solar drying model of red pepper and the kinetics of pure water evaporation (I and II),” Drying Technology, Vol. 15, Nº 5, pp. 1419-1432 and 1433-1455, 1997.

Rela, A.: Desarrollo de los solarímetros SC1 y SC2. Departamento de Radiación Solar, ONFC, San Miguel, 1975.
Saravia, L; Alanís, E.; Fabris, A. and Souto, J.: 2ª Reunión de Trabajo de Energía Solar, Tomo I y II, 1976.

Departamento de Ciencias Exactas, Universidad Nacional de Salta.
Solarcooking.org (2002): http://solarcooking.org/cookit.htm

Telkes, M.: “Solar Cooking Ovens”, Solar Energy, 1959.

Biographical Information

Victor Passamai is a full professor in the department of Physics at the National University of Salta in Argentina. He has vast experience in the field of solar cooking and drying and has written several papers in the last ten years. He was also a Fulbright visiting scholar at the University of Illinois at Urbana-Champaign in the fall of 2001.

Jorge L. Alvarado is an assistant professor of engineering technology and industrial distribution at Texas A&M University. His research interests include applied thermal sciences and fluid mechanics. He has also done research in the area of *design for the environment* as well as in fundamental heat transfer. He completed his dissertation at the University of Illinois at Urbana-Champaign in the fall of 2004.