Solar Drying in Africa

Proceedings of a Workshop
held in Dakar, Senegal,
21-24 July 1986

Editors: Michael W. Bassey and O.G. Schmidt
Abstract -- This book presents the proceedings of a workshop on solar drying in Africa attended by 24 participants involved with solar drying research relevant to the continent. Of the papers, 17 describe research activities on socioeconomic aspects, design and testing of solar dryers, and future research needs. In addition, a summary of the discussions held during the workshop to assess the state of the art of solar drying research in Africa are outlined, focusing on progress made and on possible research and collaborative activities that are needed to overcome the technical and socioeconomic problems that limit the development and introduction of improved solar dryers.

Résumé -- Voici le compte rendu d'un colloque sur le séchage solaire en Afrique auquel participaient 24 personnes effectuant des travaux de recherche propres à ce continent. Au nombre des communications, 17 décrivent les activités de recherche sur les aspects socio-économiques, la conception et l'essai des séchoirs solaires, ainsi que les besoins futurs de recherche. En outre, le lecteur trouvera un résumé des discussions sur l'état de la recherche sur le séchage solaire en Afrique, notamment les progrès réalisés et les activités de recherche coopératives nécessaires pour surmonter les problèmes techniques et socio-économiques qui entravent la mise au point et la diffusion de séchoirs solaires améliorés.

Resumen -- Este libro contiene los trabajos presentados en un seminario sobre secamiento solar en Africa, al cual asistieron 24 participantes del área de investigación en secamiento solar referida a este continente. Diez y siete de los trabajos versan sobre actividades de investigación en aspectos socioeconómicos, diseño y prueba de secadores solares y necesidades futuras de investigación. Se describe además la discusión sostenida durante el seminario para sopesar el estado de la investigación en secamiento solar en Africa, discusión que se centró en los progresos realizados y en las posibilidades de investigación y acciones colaborativas necesarias para superar los problemas técnicos y socioeconómicos que obstaculizan el desarrollo y la introducción de secadores solares mejorados.
## CONTENTS

- Foreword ................................................................. vii
- Acknowledgments ...................................................... ix
- Introduction ............................................................. 1
- Discussion and recommendations ................................. 6
- Potential improvements to traditional solar crop dryers in Cameroon: research and development Charles J. Minka .......... 11
- Influence of technological factors on the rate of drying of vegetables using solar thermal energy Emmanuel Tchiengue and Ernest Kaptouom ...................................................... 23
- Outlook for solar drying of fish in the Gambia A.E. N’Jai ...... 34
- Circulation of air in natural-convection solar dryers Herick Othieno ................................................................. 47
- Solar energy research for crop drying in Kenya F.B. Sebbowa .... 60
- Solar drying in Mali Modibo Dicko .................................... 75
- Potentials and performance studies of solar crop dryers in Mauritius Y.K.L. Yu Wai Man ...................................................... 92
- Design and tests of solar food dryers in Niger Yahaya Yaou, Zabeirou Radjikou, and Jean-Marc Durand ............................. 107
- Solar energy for crop drying in developing countries E.A. Arinze ................................................................. 128
- Evaluation of three types of solar dryers for Nigerian crops J.C. Igbeka ................................................................. 162
- Appropriate technology for solar fish drying in artisanal fishing centres Niokhor Diouf ...................................................... 175
- Some results from solar drying tests at the Centre national de recherches agronomiques Hyacinthe Modou Mbengue .................... 194
- Problems and solutions for natural-convection solar crop drying Michael W. Bassey, Malcolm J.C.C. Whitfield, and Edward Y. Koroma ...................................................... 207
A numerical model of a natural-convection solar grain dryer: development and validation  P.H. Oosthuizen  ......................... 234

Solar drying problems in Togo  K. Amouzou, M. Gnininvi, and B. Kerim  ................................................................. 252

Research and development on solar drying: advancing energy supply options or meeting felt needs  Charles Y. Wereko-Brobby  .. 272

Workshop participants  ................................................................. 285
PROBLEMS AND SOLUTIONS FOR NATURAL-CONVECTION SOLAR CROP DRYING

Michael W. Bassey,1 Malcolm J.C.C. Whitfield,2 and Edward Y. Koroma3

Abstract — Solar crop drying is an important postharvest practice in African countries. Traditional practices are known to have several drawbacks that can be eliminated using solar energy as a heat source in improved drying systems. Unfortunately, these solar dryers have not yet made any significant impact in rural areas. This paper discusses the prerequisites for the development of natural-convection solar crop dryers, using experience from research activities in Sierra Leone. Studies critically discussed include: initial needs assessment; climatic conditions and available energy sources; experimental studies on hybrid and solar dryers, pointing out useful contributions made and constraints in their design; activities to consider during field testing; and possible areas for improving research in solar drying. Substantial experimental work done in Sierra Leone on solar dryers provides some insight on their operation. These results on chimney design, drying curves, air heater configurations, airflow improvement, etc. should be supported by analytical work. Although more concerted technical effort is required before solar dryers can be effectively used, it is pointed out that success is dependent on cost and effective field testing, using an interdisciplinary team.

Introduction

Drying is an important process used in nearly all developing countries to preserve both food and nonfood commodities. Traditional methods of drying, although satisfactory in some cases, suffer from certain drawbacks, particularly exposure of the commodity to rain, dust, birds, and rodents and improper and inadequate drying, which lead to inferior products. For certain foodstuffs, improper drying causes the development of aflatoxin and other toxic moulds that are detrimental to human and animal health.

1 International Development Research Centre, BP 11007, C.D. Annexe, Dakar, Senegal.

2 Department of Mechanical Engineering, University of Sierra Leone, Freetown, Sierra Leone.

3 Rice Research Station (Rokupr), P.M.B. 736, Freetown, Sierra Leone.
The need to improve traditional drying and thus to improve product quality and the quantities that can be handled is generally agreed. Because of the various flaws in traditional drying, interest has, in the last decade, been focused on the design and use of improved drying systems, mainly for foodstuffs, using solar energy as a heat source. Although some of the solar dryers show promise for rural applications, they have unfortunately not found widespread use in developing countries for several reasons.

Several studies have been done in Africa to develop solar dryers for commodities such as timber (Okoh 1985), rice (Bassey 1982b), onions (Ba et al. 1982), vegetables (Ali and Sakr 1982), pyrethrum (Sebbowa 1985), maize (Johnston 1984), and fish (N'Jai 1985). Other studies have been concerned with assessing the nutritional values of dried food (Gomez 1982) and improving dryer performance (Bassey 1982a, 1985a; Whitfield 1985a; Othieno 1985).

Despite the contributions made by these researchers and many others, solar dryers are not widely used by farmers in Africa. In our opinion, the reasons for this are sixfold.

- A general lack of preliminary studies before a dryer is built to identify the commodities that must be dried;
- Improper sizing of the dryers to match the farmer's needs, which makes their use uneconomical or inappropriate;
- High capital cost of the dryers due to the low income of most rural farmers;
- Poor performance of the dryers as a result of design flaws;
- Low airflow through the dryers, because air is circulated by natural convection (electricity or other energy forms to increase airflow are not available in most rural areas); and
- Improper or insufficient testing of the developed dryers by the intended users.

Proper planning of research activities in solar drying is, therefore, needed to obtain valid results that will lead to the widespread use of improved drying systems.

Considering the points raised above, we discuss here those approaches that could be adopted by workers involved in solar drying research and development for application in Africa. To make the presentation practical and relevant to Africa, we use examples of research work carried out in Sierra Leone over several years. Only natural-convection solar drying is discussed here.

Initially, we review those studies that should be carried out before a dryer is designed, i.e., what crops are to be dried and how much energy is available to dry them. The design, development, and operation of solar drying systems and the related problems are also discussed. Finally, we suggest areas for further research activities and the strategies that should be used to obtain useful results.
Drying Requirements

Problem Identification

In practice, the first step in developing improved solar drying is to identify the specific problem. Taking into account the scarcity of funds, both from national and external sources, the problem should usually be of national importance and its solution should be economically viable.

To correctly identify a drying problem, the people experiencing it must first be contacted. Studies on solar drying were initiated in Sierra Leone as a result of the involvement of one of the authors in a country-wide rural-technology survey to identify traditional technologies that needed improvement. Contacts with various farmers indicated that, although traditional drying yielded satisfactory results, useful changes could be made. Although it was then difficult to determine precisely what commodities would benefit from improved drying, those initial contacts with farmers did show their concern and wish to improve the drying of their crops.

Assessment of Needs

Many solar-drying projects have been based on only superficial identification of a drying problem. Such an approach is unsatisfactory and could easily lead to a solution that is useless to the intended beneficiary.

Having established that certain crops might benefit from improved drying, a survey was carried out throughout Sierra Leone to obtain more detailed information on target crops and on the farmers' views and experience. Based on knowledge of areas of agricultural activities and within the limits of public transportation and human resources, the survey areas were chosen as shown in Fig. 1. The questionnaire used was designed by one of the authors (a mechanical engineer) with no social scientist's input. The enumerators were 3rd-year mechanical engineering students who could speak the languages of the various areas visited. They were well briefed concerning all aspects of the survey. Farmers participating in the survey were randomly chosen and the enumerators were supervised in the field by one of the authors and a research assistant.

Although the method adopted for the survey gave satisfactory results, certain aspects could have been better organized: for example, the questionnaire was prepared without the input of a socio-economist. This is a common practice in projects that develop technologies for use in rural areas: it is also a practice that should change, however, certain constraints limit interdisciplinary collaboration.

Many socioeconomists in Africa are removed from the rural environment and, at the same time, their interest in the development of technology has until recently been limited. Engineers or physicists, on the other hand, either are unwilling to solicit the participation of socioeconomists or do not know how to interact with them. In the case of this survey, the constraints of time and lack of transport made it difficult to interact with agricultural economists and other
Fig. 1 Areas where survey on traditional drying was carried out and locations where meteorological data were obtained, Sierra Leone.

nontechnologists who could have had valuable input during the preparation of the questionnaire and the field work.

Because the enumerators were chosen from their home districts, it was relatively easy to obtain reliable information from the farmers. In addition, the familiarity of the enumerators with the needs of both the farmers and the survey made a very important contribution to the success of the survey.

Typical Results of Survey

The questionnaire used was simple to implement. About 700 copies were filled for various crops and the data have been analyzed and reported (Bassey 1982b). Typical results are briefly discussed below.

Three methods of drying the crops were identified during the survey: in the open air, over a fire, or in-storage in traditional silos. Open-air drying was the most important method used although about 20% of farmers used fire: the actual value depended on the
specific crop. Although most of the farmers were generally happy with
the traditional methods of drying they were using, they wished to have
a better quality product for most crops. They wanted to reduce drying
times and losses when handling rice, the crop cultivated most fre-
quently by farmers (Fig. 2).

Other results obtained from the survey were: the percentage of
farmers (for the total for each crop) cultivating various land areas;
the quantities of the various crops being dried by the farmers; losses
for each crop as perceived by the farmers; the duration of drying for
each crop; the amount farmers were willing to pay for improved drying
systems for various crops; and the percentage of farmers who cultivate
the various crops for sale or household consumption. Such results
provide a starting point for the development of solar dryers. In
Sierra Leone, most crops surveyed are harvested during the dry season,
I.e., October to May (Fig. 3). Based on the survey data, the needed
capacities of the dryers can be determined to allow for the economic

![Fig. 2. Percentage of farmers interviewed who
cultivate a given crop.]

<table>
<thead>
<tr>
<th>Crops</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cacao</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coffee</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundnuts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Millet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pepper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ginger</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sorghum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sesame seed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 3. Period of harvest for various crops in Sierra Leone.]}
viability of a given drying system. In addition, results of such a survey indicate the possibility of using a dryer for more than one crop to maximize its use.

Although the usefulness of a needs assessment survey is unquestionable, the results may prove to be quite frustrating if the questionnaire has not been adequately designed. Too many or too few questions may be asked during the interviews. For example, a lengthy questionnaire may result in great effort being necessary during data reduction especially if a computer is unavailable, as in the case reported by Bassey (1982b). Where possible, someone experienced in analysis of survey data should be involved in the design of the questionnaire and interpretation of results.

The improper sizing of solar dryers and high capital costs, mentioned earlier as two of the reasons for the lack of application of these technologies, can be partly resolved through an initial survey of the farmer's needs and views. This approach has not been routinely adopted by researchers, as mentioned earlier, partly because it is a time-consuming and frustrating exercise and needs reliable staff as well as transport facilities.

For Sierra Leone, the results indicate that rice, cacao, and coffee are three of the main crops (Fig. 2) that can benefit from improved drying. In view of the national importance of rice, work has been focused on developing improved drying systems for this grain. Cacao and coffee are primarily export crops.

Drying Characteristics and Quality

The interdisciplinary nature of solar drying is often underestimated. Once a crop has been identified for solar drying studies, certain information must be obtained before an appropriate solar-drying system can be developed. Some of the basic information is:

* Moisture content of the crop before drying starts;
* Equilibrium moisture content of the crop at the storage temperature;
* Maximum allowable temperature of the air and duration of continuous exposure to this temperature;
* Influence of the rate of drying, exposure to solar energy, and air temperature on the nutritional and organoleptic quality of the crop; and
* Pretreatment necessary for the crop.

Information on these aspects of the research must often be obtained with the help of food scientists, microbiologists, etc. Although published data on many crops often exist, particularly on the moisture content of harvested crops, and can reduce the work that must be done, little work has been done on drying characteristics and quality of crops in Sierra Leone. In the case of rice, which has been of interest for some time, more information is available in the literature. Experience indicates that it is of the utmost importance, first of all, to understand the drying characteristics of the crop and
then design the dryer to process the crop under the optimum drying conditions. Failure to do this may result in a product that is inferior to that produced with traditional drying.

**Climatic Conditions and Available Energy**

Knowledge of the climatic conditions and availability of solar energy is a prerequisite in solar drying. However, reliable meteorological data in many countries in Africa are often difficult to find because of lack of equipment, poor maintenance, and unreliable staff. Sierra Leone is no exception and, although several meteorological stations do exist, their state is far from being satisfactory. They are not well maintained and certain important equipment is unavailable. Furthermore, the available records of climatic data are not in a form that can be used readily.

**Climatic Data**

A study has been carried out to organize certain meteorological data available from several stations throughout the country. This involved visits to eight meteorological stations (Fig. 1), where data were obtained for 1970-1980. From the data, monthly mean daily values for maximum and minimum temperatures, relative humidities, number of rainy days, and sunshine duration were deduced and have been fully reported (Bassey 1982b).

The variation of the various climatic parameters shows that the operation of solar dryers within the country is location specific. Inland areas tend to have higher sunshine duration, higher solar radiation, and lower relative humidities compared with coastal areas. Sunshine duration is about 6-9 hours during November-April, the dry season, compared with 2-4 hours during May-October, the rainy season. Relative humidities are about 80% throughout the year.

**Solar Radiation**

There is effectively no information on solar radiation apart from that reported by Bassey et al. (1978) and Bassey (1982b). The former study attempted to use measured solar radiation obtained with Gunn-Bellani equipment in a single location to determine an appropriate formula for predicting total solar radiation for the country. However, because the solar-measuring equipment had not been maintained, the measured total solar radiation values were grossly in error and gave values for desert areas! The second study used climatic data for 11 years and limited data on measured total solar radiation to predict solar radiation for specific locations throughout the country (Fig. 4).

Although these results allow useful work to be carried out on solar dryer design, reliably measured solar radiation data for at least 5 years are still needed. This can, however, only be achieved with equipment that is powered by batteries, because the electricity supply in the country is unreliable. The locations and numbers of such equipment need to be carefully determined so that useful isoradiation maps can be developed.
Fig. 4. Estimated monthly mean daily total solar radiation for various locations in Sierra Leone. Note: values for Mount Aureol frequently coincide with those for Lungi.

Auxiliary Heat Sources

Based on the survey and on climatic data for Sierra Leone, it appears that solar energy alone may be insufficient for drying certain crops effectively during certain periods. Efforts have, therefore, been made to investigate a simple method of burning waste material such as sawdust in a burner (Bassey 1983a). The method of burning the sawdust consists of making a vertical hole through the packed material, lighting and allowing the material inside the hole to burn (Fig. 5). Results reported by Bassey (1983a) consisted of mathematically characterizing the burning process and developing equations that could be used to design burners for various applications. This burner has been used to produce heat to operate various types of equipment, including a hybrid crop dryer (Bassey 1983b, 1985b).

Solar energy, being intermittent in nature, cannot satisfy all drying needs. However, few attempts in African countries have been made to investigate auxiliary systems to aid solar drying. The use of a supplementary source of heat cannot be economical in many cases, e.g., for very small-scale applications, because of the initial capital investment needed, but for larger drying systems the volume of the crop may justify such a system.

Equipment Design and Development

Design Information and Constraints

Most solar dryers are designed without considering the commodity to be dried. In many cases, a dryer is built first and then tested to determine how well it dried various crops. Furthermore, dryers are built with little consideration of such meteorological conditions as ambient relative humidities, air temperatures, and solar energy
availability. Thus, solar drying could be considered as "a technology looking for a problem" rather than "a technology developed to solve a problem." This approach must be changed.

The information needed to design a solar drying system must be obtained at the farm level, from meteorological stations, and from the literature. Problems in design arise from the need to keep the cost of the dryers low to match the low income of the potential users because imported materials needed in the design are expensive. A further design constraint is that electricity is expensive and generally unavailable in most rural areas so that most dryers cannot use fans for circulating the heated air. Even with these constraints, useful solar crop dryers can be designed (Bassey 1982c).

Solar hot-air collectors and drying chambers in which air is circulated by means of a fan are designed routinely. However, where natural circulation is used, designs have presented problems due to their low airflow rates. Satisfactory design procedures for indirect natural-flow dryers are lacking because the fluid-flow and heat-transfer processes involved during operation of these dryers, as a means of matching airflow rates and air temperatures through the crops, have not been actively investigated by researchers.

Work on solar dryer design in Sierra Leone has concentrated on using supplementary heat sources, improving airflow rates, utilizing local materials, and understanding the operation of indirect natural-flow solar dryers. These are considered to be areas where significant progress can be made.

**Hybrid Dryer**

Various aspects of the design and operation of the hybrid dryer have been reported (Bassey 1985b) but are discussed briefly here. The dryer has two main elements, the actual drying cabinet and a sawdust burner to produce supplementary heat (Fig. 6). The dryer consists of a direct solar dryer cabinet designed to operate under load at temperatures up to about 70°C so that a wide range of crops can be dried.
It was designed using the knowledge of incoming solar radiation, amount of water to be evaporated from typical crops, the design procedure for the sawdust burner (Bassey 1983a), and basic heat-transfer principles. It was assumed in the design that the energy input by the burner to the drying cabinet was 400 W/m², burner efficiency to convert water to steam was 10%, condenser efficiency was 50%, and a load of sawdust would burn for 4 hours.

The drying cabinet is constructed of plywood (1.25 cm thick) with double walls that are separated by a 10-cm thick layer of wood-shaving insulation. Holes (2.5 cm diameter) were drilled in the bottom of the cabinet and near the top of the vertical walls to allow air to enter and leave the dryer. Crops to be dried were placed on three trays that could be inserted and withdrawn through a door at the back of the dryer. The top of the cabinet was covered by a single glass cover (0.16 cm thick) with an area of about 2 m².

The burner consisted of 28 burner holes (2.5 cm initial diameter), spaced at 10 cm between centres, and arranged in four rows. Four galvanized iron pipes (110 cm long, 2.5 cm diameter) were mounted directly over the burner holes. Water in these pipes was evaporated and the steam passed through the heat-exchanger pipes in the drying cabinet and then vented to the atmosphere.

Tests were carried out on the dryer under no-load conditions and under load using okra (Hibiscus esculentus L.). Results indicate that the hybrid dryer performs very satisfactorily, giving a range of working temperatures depending on the combination of heat sources used.
Under no-load conditions (Fig. 7), the hybrid dryer reached satisfactory working temperatures using solar energy alone, sawdust
alone, or combined solar energy and sawdust. Thus, on days when the solar availability is good (Fig. 7b), it may not be necessary to use a supplementary heat source. However, when the solar radiation is low, the auxiliary burner must be used to maintain a high enough cabinet temperature (Fig. 7a, day 3). The number of times the burner must be recharged will depend on the incoming solar radiation (for all the tests shown in Fig. 7a, the burner was only loaded twice). Using the burner alone, the dryer can be maintained at a constant temperature only if it is recharged (Fig. 7c).

The okra used for the on-load tests was cut into 1 cm pieces and loaded onto the trays; about 10 kg were dried during each test. Typical results for the three modes of heating are shown in Fig. 8. Temperatures in the cabinet during drying were highly dependent on the available solar radiation when solar energy alone is used (Fig. 8a). However, when the sawdust burner is used as a supplementary heat source, the dryer temperatures can be kept fairly constant by additional loading of the sawdust burner (Fig. 8c).

Although open-air drying can give the same rate of drying as using solar energy alone in the dryer (Fig. 8a, moisture content graph), use of solar energy and sawdust simultaneously (Fig. 8c) halves the drying time. More importantly, however, the burner allows drying to continue when solar energy is not available (simulated in Fig. 8b, moisture content, by the results for open-air indoor drying) and the okra would become mouldy and rot if it were not dried.

The quality of the dried okra was evaluated in terms of its texture, colour, and how easily it could be pounded into flour compared with the open-air-dried product. The dryer gave a greener product that was more crunchy and more easily pounded compared to open-air-dried okra. Also, mould was noticed on the open-air-dried okra whereas the product from the dryer was mould-free.

Although further quality tests should have been carried out and other crops tested on the dryer, this was not possible due to financial and personnel constraints. Efforts should be made to continue work on this dryer, however, to investigate other forms of agricultural waste that could be used in the burner and to improve its overall performance.

Indirect Natural-Convection Dryers

Natural-convection dryers consist of three main components: an air heater, a drying chamber, and a device to induce airflow. Studies in Sierra Leone have been concerned with improving chimney design to increase the flow of heated air through the crop; understanding the interaction between the various parameters influencing the operation of these dryers; and improving the design of the dryers so as to make them more appropriate to local needs. The basic dryer configurations studied are shown in Fig. 9.

Chimney Design and Airflow

Chimneys used on natural-flow solar dryers are simple cylindrical ducts attached to the top of the drying chamber. Although they are intended to increase airflow due to the warmer column of air (with respect to the ambient air outside the chimney), it is suspected that they actually reduce airflow for various reasons.
Fig. 8. Variation of temperatures in hybrid dryer cabinet and drying curves for okra for various operating conditions.
Fig. 9. Basic configuration of natural-convection dryer and air heaters used on dryers.

Studies consisted of using chimneys of various configurations and air heaters of two cross-sectional designs (Fig. 9) attached to identical drying cabinets. Temperatures were measured at various positions throughout the dryer but air velocities could not be measured because proper instrumentation was unavailable. Tests were carried out under no-load and under load using rice.

The chimneys were all made of 0.16-cm galvanized iron sheet and had an internal diameter of 15 cm. The following five types were tested: 38 cm high, unpainted, painted black outside, or painted black...
outside and surrounded by transparent plastic; and 180 cm high, painted black outside or painted black outside and surrounded by transparent plastic. Where a plastic cover was used, the air gap between the plastic cover and the chimney surface was 2 cm.

Results of this work have been reported and discussed by Bassey (1982a, 1985a). Because no airflows were measured, temperatures in the dryer cabinet were used to indicate the performance of the chimneys. From the data obtained over a 3-year period, mean solar radiation intensities are plotted against mean temperatures in the drying chamber under no-load conditions (Fig. 10).

Although there is considerable scatter due to cloud cover, different chimneys gave different temperatures. For a given height of chimney, the dryer using the air heater with a single air passage (dryer I) gave the highest cabinet temperatures when the chimney was painted black, and then covered with plastic. Taller chimneys on dryer I give lower temperatures. In dryer II, which has two air passages, dryer temperatures decreased progressively with black paint and plastic covering. Increasing the height of the chimney increases the dryer temperatures.

The responses (Fig. 10) have been explained by possible increases and decreases in air mass flow resulting from the heat gained or lost by the chimney (Bassey 1982a, 1985a). Also, the temperatures in the dryer beneath the crop are substantially higher than those in the chimney, due to the moisture removed from the crop by the air. This results in reduced airflow and makes the dryer inefficient.

Therefore, because of the intermittent nature of solar energy and prevailing ambient conditions, tall black chimneys should only be used under clear sky when there is little or no wind and ambient temperatures are high. Shorter chimneys covered with a transparent cover are suggested for cloudy, windy environments to minimize heat loss from the chimney. Such chimneys may also be useful at higher latitudes for heating the air inside them so as to increase the buoyancy force.

Although these results have helped in gaining some insight into the possibilities of improving dryer design, they should not be considered conclusive. Mass flow rates must be measured to support arguments presented.

Parameters Affecting Dryer Performance

In addition to work on chimney designs, studies have been done to obtain a better understanding of the performance of indirect solar dryers under various conditions.

Comparisons between the two air heaters shown in Fig. 9 have suggested that a simple heater with a single passage may be adequate for natural-flow dryers (Bassey 1985a). Useful data on the effect of solar radiation on temperatures at various positions in these dryers are also available for further design work. In addition, the relative performance of the dryers investigated in drying various thicknesses of rice beds have been documented (Bassey 1982b).

It should be mentioned that some results for the variation of
moisture content of rice with time show substantial scatter in the data points especially when the rice bed is deep (Fig. 11). This is due to the sampling procedure used. During experiments, the rice bed was thoroughly mixed before each sample, consisting of a few grams,
was taken for moisture-content determination (using the oven method). However, some of the samples were probably representative of grain either at the bottom of the rice bed (where the rice was quite dry) or at the top of the bed, where the rice was wetter. Because the samples chosen were very small compared to the bulk of the rice in the dryer, scatter was observed in the data. (This phenomenon has also been observed in various results reported in the literature.)
More reliable moisture-content results could be obtained by weighing the whole bulk of the rice during experiments. However, such a technique would entail relatively sophisticated equipment that was not available when the tests were being conducted.

Despite these apparent inaccuracies in moisture-content data, the results have been satisfactorily used in the development of numerical simulation of the performance of indirect natural-convection dryers (Oosthuizen et al. 1985).

Studies in Sierra Leone indicate that the operation of natural-flow indirect solar crop dryers under conditions of changing cloud cover is very complex. Although cloud cover causes some scatter in the data, it is possible to correlate the mean daily temperatures in the dryer to the mean daily intensity of radiation. Such information allows similar dryers to be compared.

In general, the temperatures of the air underneath the crop are increased compared to the no-load condition. Also, the temperatures above the crop are substantially different from those below it and often close to ambient conditions. These observations suggest that the assumption of a uniform density of air throughout the dryer during design may need to be reconsidered.

Dimensioning of Natural-Convection Dryers

Using experience gained from work where a basic dryer design was specified (Bassey 1982b), further work has been done in Sierra Leone by Whitfield (1985b) to optimize various dimensions of the dryer for optimum flow rates of air. In this case, however, temperatures were measured at various positions in the dryer and air velocities were measured inside the chimney under no-load conditions. The results allowed the effect of heating, cooling, and insulating a chimney to be explained. Detailed measurements of mass flow rates and temperatures under load are, however, needed to substantiate the explanations that were based on no-load tests. However, because of the complex relationships among all governing parameters, it is difficult to be positive about any explanations that are based only on experimental work or to use such studies to optimize the dimensions of dryers.

Insulating the dryer cabinet with a 7-cm thick layer of wood shavings increased the mass flow rate of air only slightly under no-load conditions (Whitfield 1985a). More measurements under load are required to support these observations.

No-load tests were carried out to find the optimum diameter for the chimney using the dryer configuration shown in Fig. 9 with heater 1 (Whitfield 1984a). Mass flow rate increased with larger chimney diameters (Fig. 12). Although these results show that the chimney diameter should be increased, experiments under load would have been more useful. However, the tedious nature of taking such data under the existing conditions (without data-acquisition systems) during the tests was a constraint.

Earlier work (Bassey 1982b) led to the recommendation of an air heater such as that shown in Fig. 9, that has a single air passage 4 cm high. This configuration was derived using simple heat-transfer and fluid-flow formulations and assumptions based on experience with
In the operation of natural-convection dryers. Another recommendation for the dimensions of dryers is that the surface area of the transparent cover on the air heater should be equal to the horizontal area of the drying chamber. In addition, it has been recommended (Bassey 1982a, 1985a) that chimneys should be short (less than 40 cm) and insulated to prevent heat loss to the ambient air. Results of other studies (Whitfield 1985b) suggest that the cross-sectional area of the chimney should be more than 16% of the horizontal area of the drying chamber.

In the absence of reliable methods for sizing dryers, these recommendations can be used as guidelines. Better relative dimensions of various parts of natural-flow dryers could be obtained using computer modeling, which minimizes the amount of experimental work needed.

Construction Materials

One of the constraints in obtaining an appropriate dryer is the high cost of materials. Various suggestions have been made concerning the choice of materials (Bassey 1982c), but the rapidly changing economy in a country such as Sierra Leone creates a situation where an appropriate design today may be inappropriate in a few months because the materials are lacking or cost too much.

Experience in solar drying in this country shows that the use of plywood, glass, and galvanized iron as the main construction materials is inappropriate at present because of their high cost. Therefore, the capital cost of dryers has been reduced by making them out of mud.
or clay bricks. A design now being tested uses these blocks for the sides of the dryer, straw as the insulation in the air heater, galvanized iron as the absorber plate, and glass as the transparent cover. This dryer (Fig. 13) will substantially reduce the capital cost but needs to be tested to determine the influence of its thermal mass on its performance. The drying chamber in this dryer is 90 x 90 x 180 cm long; the chimney is 22 cm in internal diameter and 150 cm high; the solar collector covers 180 x 90 cm² and is inclined at 20° to the horizontal facing south.

This dryer was used to test the effect of using various transparent material as the collector cover (Fig. 14). Although transparent materials other than glass would be cheaper, the temperatures obtained in the solar collector using polyethylene (plastic) or fibreglass are substantially lower than those using glass and drying was slower. Further work is in progress to assess the advantages of this low cost dryer.

Fig. 13. Natural-convection dryer made from mud bricks.
Fig. 14. Dependence of performance of mud brick dryer on type of transparent cover used.

Field Testing

In Sierra Leone, there have been no meaningful tests of solar dryers among the rural farmers: this is also generally true for most other African countries. In some countries, such as in Sierra Leone, research and development (R&D) have not yet produced suitable solar dryer designs whereas, in others, researchers are either reluctant to venture out into villages or are ignorant of what approaches to take.

Assuming that a dryer design has been obtained based on the needs of the intended beneficiaries and the R&D personnel involved have the will to carry out field work, certain basic guidelines must be followed to ensure that the dryer is properly tested under real-life conditions. Experience suggests that, because this activity is interdisciplinary, the team should consist at least of a technologist, a socioeconomist, and one or more extension workers. The choice of the test sites depends on the availability of crops, receptiveness of the beneficiaries to change, and their enthusiasm to participate. Throughout the field testing, the technologist and the socioeconomist should visit the field sites regularly to make spot checks.
Although the list of eight events outlined below is by no means complete, we believe that it gives a framework for carrying out field testing:

- Choose appropriate dryer design;
- Choose sites for field testing with the help of extension workers and socioeconomists;
- Install or build dryers with the active participation of beneficiaries and extension worker;
- Assign extension workers to monitor dryer operation and user reaction;
- Prepare questionnaire to be used during field testing to cover technical performance, economics of drying, and user reaction;
- Allow the user to operate the dryer in comparison with traditional drying. Basic data such as weight of crop before and after drying, and drying time should be collected by extension worker. Testing should ideally last for at least a drying season;
- Modify the drying system, if needed, during field testing; and
- Evaluate the results to assess technical performance, economic viability, and social acceptability.

The importance of field testing within an R&D program should not be underestimated because it is through this activity that a true assessment can be made of the suitability of the developed solar dryer. A substantial effort must be made by African researchers to introduce drying systems among the rural users. Without this intervention, the present situation of having dryers remaining in laboratories can be expected to continue.

**Potentially Useful Dryers**

The work in Sierra Leone on solar crop drying indicates that it would be more economically advantageous for a dryer to dry more than a single crop during most of the year. However, because solar energy would be inadequate on a year-round basis to produce the required heat, hybrid dryers may, in some cases, be appropriate.

The hybrid solar/sawdust dryer and the natural-convection indirect dryer described here could be developed for use in several countries in Africa. Such developments must, however, be rapid because of the changing economic situation. For example, these two dryers were within the financial reach of some farmers about 5 years ago when they were constructed from plywood, galvanized iron, and glass. Hardly any farmers will buy these dryers today because of the high cost of materials, which have increased 10-fold in some cases.

In Sierra Leone, work is actively in progress to use the indirect solar dryer for drying rice and farm testing is expected by early 1987. However, field tests of the hybrid dryer are not planned because more work is needed to use low-cost materials.
Future Research on Solar Drying

Work carried out in Sierra Leone suggests that further research is needed to improve solar drying. These activities, the assessment of drying needs, laboratory work, and the field testing of prototypes, are outlined in the following sections.

Assessment of Drying Needs

Although a study on the farmers' perception of their drying needs has been carried out in Sierra Leone, further surveys are necessary to obtain a more complete understanding of the drying problem. For example, studies are needed to estimate quantities of crops that must be dried, their geographical distribution, losses in income due to inadequate drying, assessment of the capability and willingness of farmers to acquire a drying system, possible dryer capacities, and the possibility of improving farmers' income through the introduction of improved drying systems.

Because they are multidisciplinary, these initial studies must involve both socioeconomists and technologists. Farmers must also be sensitized to the potential benefits of improved drying.

Laboratory Research

The nutritive values of crops and the effect of drying on both these values and their organoleptic qualities should be studied. Within such research, the optimum drying temperatures and duration of drying needed to achieve the best dried product must be specified for a wide range of crops. Also, the effect of pretreatment on the quality of the crops and their shelf-life deserve attention.

During these studies, close collaboration will be needed between home economists, biochemists, and engineers.

Because it has been shown that measured solar energy data are unavailable and it is simply supplying enough heat for solar drying throughout the drying seasons, research in the following areas should be considered. First, more reliable systems to acquire solar radiation data must be installed in various parts of the country; these systems must be properly staffed and maintained. The data obtained over about 2-3 years can then be used to develop reliable methods for predicting solar radiation values for use in designing dryers. Second, work using the hole-through-sawdust type burner in the hybrid dryer should continue on improving its efficiency and extending the range of agricultural waste that can be used as fuel.

To understand the performance and to improve design procedures for indirect natural-convection solar dryers, laboratory research should be carried out in the following areas:

* To obtain detailed and accurate data on the distribution of temperatures, relative humidities, and pressures throughout the dryer;
* To obtain data on the drying curves for various crops using the depth of loading as a variable parameter;
* To develop simple design procedures for natural-convection dryers using a combination of experimental data and computer modeling;

* To develop dryers using locally available materials, such as mud, clay, galvanized iron, straw, and transparent plastics;

* To determine the effect of using high thermal capacity materials such as mud or clay bricks on the overall performance of the dryer; and

* To improve airflow through the use of heated chimneys, vortex generators, and simple mechanical devices, taking into account their location specificity.

Research methodology for field testing of solar dryers is lacking. Engineers and socioeconomists need to investigate the benefits of several approaches that might be adopted during the introduction of dryers. Some suggestions are:

* To assess the success of field testing due to the involvement of potential manufacturers, extension workers, and farmers (at an early stage);

* To determine the extent of involvement of the users and research team in the operation of the dryers; and

* To determine suitable monitoring procedures to adopt, specifying timing and the role of each person.

**Strategy for Achieving Results**

The general lack of human and material resources in Africa suggests that collaboration is necessary among researchers. Research on solar drying should be carried out in a more coordinated manner to maximize the use of the available resources. Certain suggestions that may help to promote the use of solar dryers are outlined below.

**Network on Drying**

The existing group of projects on drying should be formed into an effective network. Organizations such as the Commonwealth Science Council and the International Development Research Centre may be able to play a leading role in coordinating the activities of such a network. Each researcher should, depending on expertise, concentrate on a well-defined problem. In this way, duplication of efforts would be kept to a minimum and research activities would be complementary.

**Publication of Results**

Results of work done on drying are not usually circulated to a wide readership. Even when results are available, it is often difficult to assess the contribution of the research because of style of presentation, clarity, or lack of information. Researchers working on problems of relevance to Africa should be encouraged to make their findings available to fellow researchers through effective communication. A network on drying could coordinate the distribution of such valuable information.
Conclusion

This paper has attempted to present a critical assessment of requirements, conditions, and equipment for solar drying in rural areas in Africa using investigations in Sierra Leone as examples. The following four conclusions can be made:

* Initial needs-assessment studies are a prerequisite for the wide-scale adoption of improved drying systems.

* Solar drying research needs the involvement of personnel from various disciplines.

* Natural-convection solar crop dryers can be used effectively but substantial research and development work is needed before appropriate systems can be obtained. Main areas for future work are design with the help of modeling and experimentation followed by field testing.

* Investigations on solar drying in Sierra Leone have obtained results that have made useful contributions to the knowledge of operation of natural-flow solar dryers.

Acknowledgments -- The research reported in this paper was funded by research grants from the International Development Research Centre, Canada, and the United Nations Industrial Development Organization.

References


________ 1982b. Potential use and performance of indirect free convective solar crop dryers in Sierra Leone -- Final report, IDRC Research Project 3-P-78-0113. Department of Mechanical Engineering, University of Sierra Leone, Freetown, Sierra Leone.


________ 1983b. The use of sawdust for small-scale energy applications (Chapter 66). In Meyer, R.F., Olson, J.C., ed., The


———. 1985b. Limiting performance and potential of free convective solar crop dryers in Sierra Leone -- Interim report, IDRC Research Project 3-P-83-0107. Department of Mechanical Engineering, University of Sierra Leone, Freetown, Sierra Leone.