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The Construction and Testing of a Solar Food Drier in Zambia

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ABSTRACT

A small-scale, forced convection, indirect solar food drier was designed, built and tested in Zambia. It consisted of a novel combination of a solar collector, a tray drying cabinet, and a heat storage facility with a fan housing unit and a control unit. Cabbage, okra, and beef were dried under a variety of conditions. The equipment was flexible and adaptable and can be replicated in medium-technology countries.

INTRODUCTION

Food can be dried by a wide variety of techniques which may range from quite primitive to technically sophisticated methods. Practically all methods have in common that water is removed by a hot air stream flowing past the food. In many instances the air stream is used both as a heat transfer fluid to carry thermal energy to the food and as a mass transfer medium to remove the water in the form of vapor. Energy may also be transferred to the food by conduction or radiation or a combination of mechanisms. In general, heat must be supplied and water removed.

Drying methods may be classified according to various criteria, such as the source of the energy or the type of equipment in which the drying takes place. The term 'solar drying' implies nothing more than that the energy source for water evaporation is solar radiation; solar drying can be carried out in any type of drying equipment. Solar food drying methods can be divided into two major groups: direct and indirect. In the former, the solar radiation is allowed to impinge directly on the food, whereas in the latter the solar energy is collected and transported to the food, frequently by means of an air current. The air current may be the result of either natural or forced convection.

Open-air sun drying of food is still carried out extensively throughout the world. In this, the energy input comes from direct solar radiation as well as from naturally circulating warm air. The air currents also transport the water vapor away from the drying area; the 'equipment' consists of a field, floor, screen or net upon which the food is placed. The problems associated with this technique, such as damage and contamination from rain, insects, birds and rodents, have been mentioned by many authors including Cruess (1948), van Arsdel (1973) and Szulmayer (1978). To lessen the impact of some of these factors, the food may be placed under a transparent cover. This approach was employed by Khan (1964) and Lawand (1966) who dried food in closed containers through which air was allowed to flow by natural convection. Although the contamination problems are reduced in such covered, direct driers, substantial food damage is still done by the radiation. Also, the quality of food produced in direct driers is generally low because the temperature and relative humidity cannot be controlled. In an indirect solar drier the radiant energy is usually converted by means of a solar collector to sensible heat in an air stream. Food deterioration due to radiation is thereby eliminated. It is also advantageous that the drying take place within the equipment so that contamination can be prevented. The extent to which the temperature and humidity of the air stream can be controlled is a function of the complexity of the equipment. This then also largely determines the resultant quality of the food; the better the control over the drying equipment, the higher the food quality. Many authors, including Ismailova (1957), Garg et al. (1978), Bolin et al. (1978), and Kalra and Bhardwaj (1981) have described the use of indirect solar food driers.

The objectives of this project were to design, build and test a small-scale solar food drier in Zambia. The level of technology and the materials for the construction were to be limited to those generally available in the denser populated areas, i.e. near the cities and along the major roads. In these target areas, plywood, sheet metal, glass sheet, bricks, paint, and minor hardware (such as screws, nails and electrical outlets and switches) can easily be bought. Electricity has also been installed. Electronic or pneumatic monitoring and control equipment can however not be bought or serviced locally, and hence was judged to be non-applicable technology. The drier was to be designed so as to be easy to copy and operate by local labor, yet was intended to produce food of considerably higher quality than is presently sold in most of Zambia. One of the major design objectives was to allow for flexibility in drier operation so that the temperature to which the food was to be exposed, and especially the variability of the food, could be controlled to at least a fair degree. A second design objective was to use the available energy efficiently within the technological constraints imposed.

DESIGN AND CONSTRUCTION OF THE DRIER

To assure at least a minimal food quality, an indirect, forced convection drier was designed and constructed. The air currents were induced by two small electrical fans. To dampen the fluctuations in the solar collector power output, a large thermal mass was incorporated in the drier. Thus, the temperature, velocity and, indirectly, the relative humidity of the air in contact with the food, could be controlled to a certain extent. No attempt was made to implement direct relative humidity control. In the design a modular approach was followed; the drier consisted of a solar collector, a tray drying cabinet and a thermal storage interconnected by a fan housing and a control unit. The collector, storage and tray cabinet were fairly typical; it is their use in combination, in the manner which is described, that is novel. Nine simple slide valves were installed within the fan housing and the control unit. These valves allowed the air-flow paths through the drier to be defined. The drier would thus be operated in a number of modes and submodes. All modules were designed so they only required minimal tools and skills to construct. The modules were basically rectangular boxes whose sides were fastened together with screws. To assemble the drier, the modules were stacked against and on top of each other and attached with screws. Air flowed between the modules via matching holes cut in adjoining sides. Final module dimensions could vary considerably without adversely affecting the assembly of the drier or its operation to a great extent. The drier was designed to be loaded with 5 kg of wet material per batch. Detailed design calculations were presented by Kwendakwema (1983).

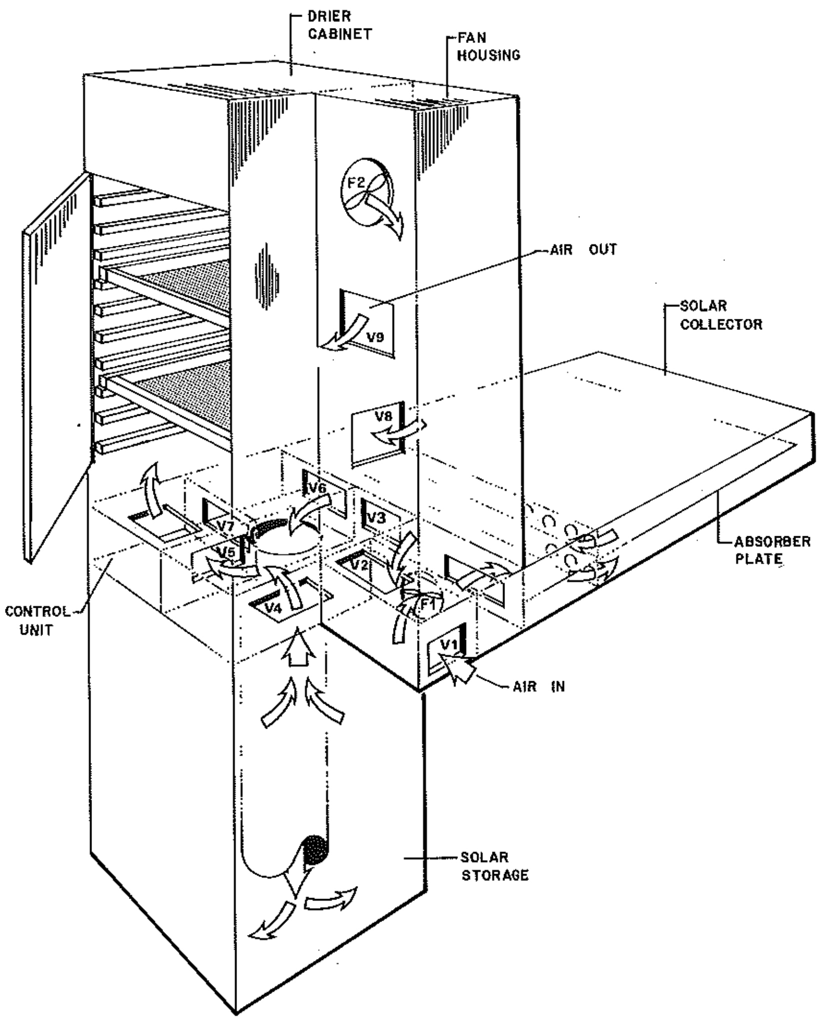

Fig. 1 Flowpaths in the drier during the heat storage mode and the total recirculation submode.

The drier is illustrated in Fig. 1. The system flow diagram is shown in Fig. 2. V1 to V9 on Fig. 2 refer to the slide valves controlling the air-flow path, T1 to T7 refer to thermometers installed in the apparatus, and F1 and F2 refer to the two fans. The drier could be operated in three main modes: (1) the straight-through mode (Fig. 2a), (2) the heat storage mode (Fig. 2b), and (3) the heat recovery mode (Fig. 2c). During any of the main operating modes, four recirculating submodes could be implemented: (a) no recirculation (by closing V2 and V8), (b) cabinet recirculation (by opening V8), (c) system recirculation (by opening V2) and (d) total recirculation (by opening both V2 and V8). The air flow path during the heat storage mode and the total recirculation submode is shown in Fig. 1. Since the valves were simple hand-activated sliding devices which could be fractionally opened, any combination of modes and submodes could also be partially implemented.

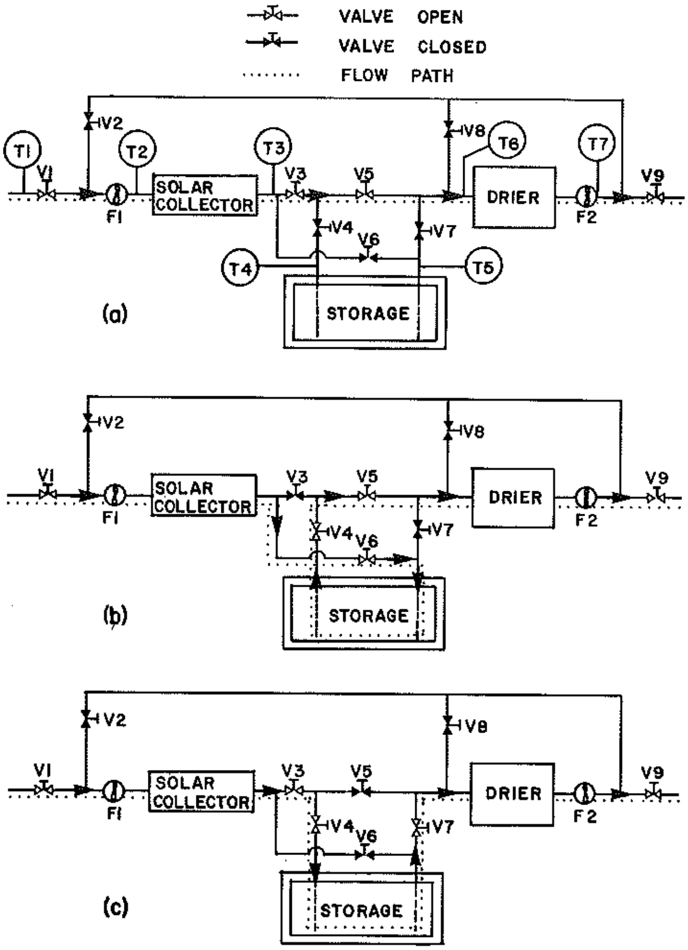

Fig. 2 System flow diagram illustrating a) the straight-through mode, b) the heat storage mode and c) the heat recovery mode.

The reason for providing the various modes and submodes was to fulfill the design objectives of energy conservation and the curtailment of the drier cabinet temperature variability. The implementation of the system recirculation submode was mainly an energy conservation measure. The cabinet recirculation submode was intended to reduce the spatial temperature variability within the cabinet by recycling the cabinet air several times during its movement through the system. As illustrated in Fig. 1, the cabinet recirculation flow path was very simple compared to the system path. The heat storage and recovery modes could be used to lessen the temporal temperature variability in the cabinet. Whenever T6 became higher than desirable, the excess heat could be transferred to the thermal storage, and whenever it fell too low, heat (if available) could be recovered.

All modules were made of plywood, 2 cm thick. The general construction procedure for the modules was as follows: (1) cut the plywood pieces into the correct dimensions; (2) paint the pieces on all sides and edges with black enamel oil paint; (3) assemble the module by fastening together the pieces with brass screws; (4) cut airflow path holes in the sides to match holes in other modules; (5) install hardware, such as fans and valves, in the module; and (6) seal all possible air leaks. General Electric Silicon Sealant was used to seal the modules internally: this was imported by the authors. Although sealant was locally available, the use of a brand whose performance is well known was preferred so as to expedite the construction and testing of this first experimental drier. This same sealing material was also applied between modules, around all matching holes, so as to assure the integrity of the air passages. The valves were made of plexiglass and were fabricated in Canada. This was done to minimize the on-site construction period. During drier assembly several of the plexiglass valves broke and new ones were fabricated locally from plywood. The body of each valve was made from two parallel plates spaced 5.1 mm apart; a third plate was slid between them. A valve was activated by pulling or pushing on a 3 mm brass rod fastened to the sliding plate. A valve is illustrated in Fig. 3. The thermometers were the mercury-column type, with a scale range of 0 to 100 °C, readable to the nearest degree. These were installed to monitor the performance of the apparatus. The two fans operated on 220 VAC and had a rated capacity of 10 m^3/min. These were acquired in Canada but were also available in Zambia. The drier was constructed and tested on the University of Zambia campus near Lusaka, Zambia. The construction phase lasted three weeks. The drier was fabricated by a carpenter working for the University of Zambia with the help of a staff member and a graduate student (the authors) during June 1982.

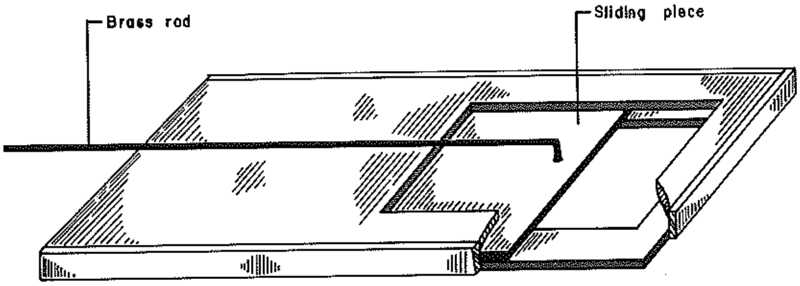

Fig. 3 A sliding valve.

The external dimensions of the heat storage unit were: 220 X 50 X 40 cm. A 5 cm thick layer of styrofoam insulation was fastened on the inside to each of the vertical walls; a 15 cm thick layer of styrofoam was placed on the bottom and covered with a false bottom to support the weight of the thermal storage material. In the resulting internal cavity (with dimensions of 205 X 40 X 30 cm), 180 kg of fired clay bricks were placed. The bricks were stacked around a 10 cm diameter, 1.95 m long aluminium air duct. The duct ended 10 cm above the false bottom. Sufficient space was left between the bricks so that air could easily flow through the stack. During the heat storage mode, hot air was forced into the lower part of the storage unit through the duct and cooled air flowed out and back into the control unit through an opening in the top of the heat storage; during the heat recovery mode the direction of flow was reversed. The heat storage unit was placed in a pit on a 20 cm thick bed of crushed stone. The rest of the pit was then also filled with this material so that the heat storage was surrounded on all sides by a substantial layer of easily draining material.

The solar collector was 5 m long, 1 m wide, and 20 cm thick. The bottom and sides were insulated on the inside with a 5 cm thick layer of styrofoam. An absorber plate was constructed of corrugated steel sheets, painted with flat black enamel paint. The absorber plate was mounted 7 cm above the bottom insulation layer. The collector was covered with a single layer of glass, 6 mm thick. The air inlet and outlet were located at the same end of the collector. Air entered below the absorber plate, flowed along the length of the collector toward the far end, where it passed through an opening between the plate and the collector end into the space between the glass and the absorber and flowed back along the length of the absorber again.

The external dimensions of the control unit were 50 X 40 X 20 cm. Inside the control unit were fastened several partitions upon which valves were mounted. In total, five of the valves (V3, V4, V5, V6 and V7) were located in the control unit.

The drier cabinet's external dimensions were 110 X 50 X 40 cm. Ten trays, each measuring 40 X 36 X 3 cm, could be placed on supports inside. The tray bottoms were steel wire mesh upon which the food was placed. Air flowed from the control unit and the fan housing into the bottom of the cabinet through a distributor plate made of plywood, then through the stack of trays, and was finally exhausted into the fan housing by F2. The trays were accessible via a door on the front of the cabinet. The door seals were made of chemical rubber tubing.

The fan housing external dimensions were 134 X 41 X 31 cm. The electric fans F1 and F2, as well as the four valves V1, V2, V8 and V9, were located in the fan housing. The air intake and exhaust, as well as recirculation took place in the fan housing.

EQUIPMENT CHARACTERIZATION – METHODS AND RESULTS

Two sets of experiments were conducted: (a) equipment characterization experiments to study the temperature histories that could be attained in the drier cabinet during operation in the various modes and submodes without food in the drier, and (b) drying experiments to determine the drying rates of several foods and to evaluate the effects of the tray position and operating the submode on the drying rates. Due to financial and time restraints, the experiments were carried out during the Zambian 'winter' (July 1982). During this season the maximum daily temperature does not usually exceed 30 °C and the minimum daily temperature may fall slightly below 0 °C. Although Zambian weather is remarkably consistent on a day-to-day basis, a certain variability was inevitable. This inevitably influenced the results.

Eight equipment characterization experiments were run. Each experiment lasted one day. For every experiment the valves V1 to V9 were set appropriately, and the fans F1 and F2 were switched on at 08:00 h. The temperatures were read on thermometers T1 to T7 every 20 minutes and recorded. The experiments were ended at 17:30 h. For the first four experiments the straight-through operating mode was used with one of each of the four submodes. For the last four experiments the submode was also kept the same during any one experiment, but the operating mode was changed twice during the day; the system was initially configured in the straight-through mode, then switched to the heat-storage mode when T3 reached 50 °C, and subsequently switched to the heat-recovery mode when T3 fell below 50 °C again in the afternoon. The operating modes and submodes implemented are shown in Table 1.

The temperature histories obtained at thermometers T1, T2, T3, T6 and T7 during experiment 1 are shown in Fig. 4. The T4 and T5 curves are not shown since the heat storage mode was not used. Although air was not recirculated within the system, T2 was always a few degrees above

Table 1
Maximum daily temperature attained during the equipment characterization experiments

Expt	Operating Modes	Recirculation Submode	Maximum Temperatures						
			T1M	T2M	T3M	T4M	T5M	T6M	T7M
1	straight-through	no recirc.	26	31	66	NA	NA	59	46
2	straight-through	system recirc.	25	48	68	NA	NA	61	48
3	straight-through	cabinet recirc.	26	36	68	NA	NA	49	46
4	straight-through	total recirc.	24	42	65	NA	NA	52	44
5	sequence of modes	no recirc.	26	30	67	45	63	43	40
6	sequence of modes	system recirc.	29	46	72	50	68	50	45
7	sequence of modes	cabinet recirc.	27	37	69	43	60	42	42
8	sequence of modes	total recirc.	33	47	73	48	68	46	44

T1. This was also observed during other experiments when V2 was closed. Some heat transfer from the apparatus to the incoming air stream probably took place in the fan housing and the air distribution section of the solar collector; there may also have been a slight leak in V2. During the experiment, T6 remained several degrees below T3 for most of the day but then slightly exceeded

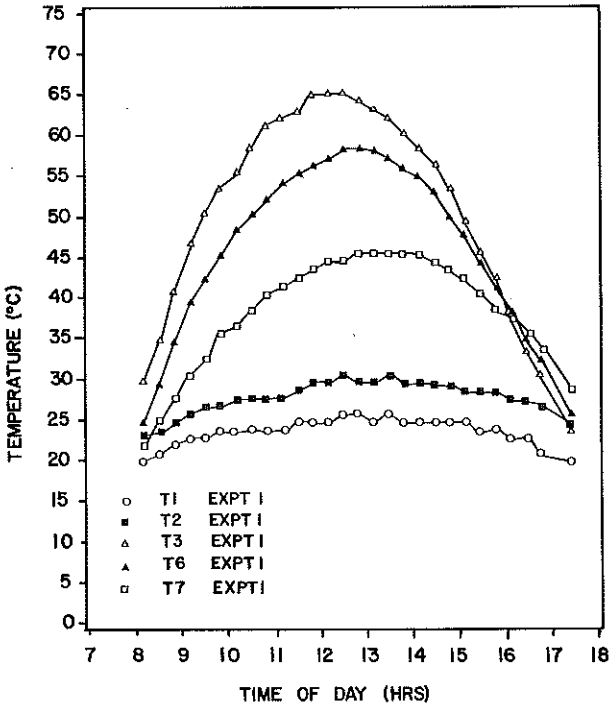

Fig. 4 The temperature-time histories obtained during experiment 1.

it at the end. The T6 and T7 histories were similarly related: T7 remained well below T6 until about 16:00 h, then rose slightly above it. Thus, substantial temperature drops were observed to occur during the convective transfer of heat from the collector outlet to the drier inlet, as well as during the passage of the air through the drier cabinet itself. Much of the decrease in temperature was undoubtedly due to heat loss to the environment. This reflected the relatively crude construction methods and materials used (e.g. the poor quality seal on the drier door and the lack of insulation on the walls of the control unit, the fan housing, and the drier cabinet). Part of the temperature decrease must also have been due to unintended heat transfer and storage within the apparatus. A part of this stored heat was recovered again when T6 rose above T3 and T7 above T6 late in the afternoon. The rather heavy construction of the equipment caused it to have a considerable thermal capacitance, the price to be paid for sturdiness. As had been anticipated, with straight-through operation and no recirculation, the temperature varied considerably within the cabinet as well as throughout the day. Presumably, both spatial and temporal variabilities were somewhat less than they might have been, as a result of the unintentional storage of heat in the apparatus and small leaks in the valves, giving rise to a certain amount of recirculation.

The maximum values of T1 to T7 obtained during the eight equipment characterization experiments are shown in Table 1. These maxima are referred to as T1M to T7M below. The extent of the day-to-day variability of the meteorological conditions may be inferred from the T1M values; these varied from 24 to 33 °C. Based on straightforward physical considerations, the relationship between the ambient temperature and system performance would be expected to be complex. To gain some appreciation of the extent to which the ambient temperature may have influenced the experimental results, a simplified approach was followed wherein only the maximum temperatures were taken into account. The general effect of the ambient temperature upon the other temperatures may thus be gauged by comparing results from experiments which were similar. Experiments 1 and 5 differed only in that heat storage was used in the latter but not in the former; in neither experiment was air recirculated. The T1M values were both 26°C; the T2M values were 31 and 30°C, and the T3M values were 66 and 67°C respectively. In this instance the apparatus performed similarly under like conditions. The same can be said when the results of experiments 3 and 7 are compared: the T1M values were 26 and 27°C, the T2M values were 36 and 37°C, and the T3M values obtained were 68 and 69°C respectively. The conditions under which experiments 2 and 6 were run were however somewhat different – in that the T1M values were respectively 25 and 29°C. Correspondingly, the T3M values also differed by 4°C, being respectively 68 and 72°C. Similar diferences are again found between experiments 4 and 8: the T1M values were 24 and 33°C, and the T3M values were 65 and 73°C respectively. As might be expected, in general T3M varied directly with T1M. When system recirculation was not used, T2M also varied directly with T1M. When however, system recirculation was implemented, i.e. during experiments 2, 4, 6 and 8, this was not always true; the recirculated air flow was mixed with the incoming air, thus creating a more complex pattern of interaction between the variables. Since most of the other temperatures in the system depended either directly or indirectly on T3, presumably they were at least to a certain extent affected by the ambient temperature.

In Fig. 5 the temperature histories observed at the bottom of the drier cabinet (T6) during experiments 1, 2, 3 and 4 are shown. When heat storage and recovery were not implemented, the effects of the various submodes were that system recirculation increased T6 (experiment 2 vs. 1), that cabinet recirculation lowered T6 (3 vs. 1) during most of the day, and that a combination of the two recirculation methods yielded an intermediate result (4 vs. 1). A similar pattern is exhibited by the T6 histories of experiments 5, 6, 7 and 8, which are compared in Fig. 6. An increase in

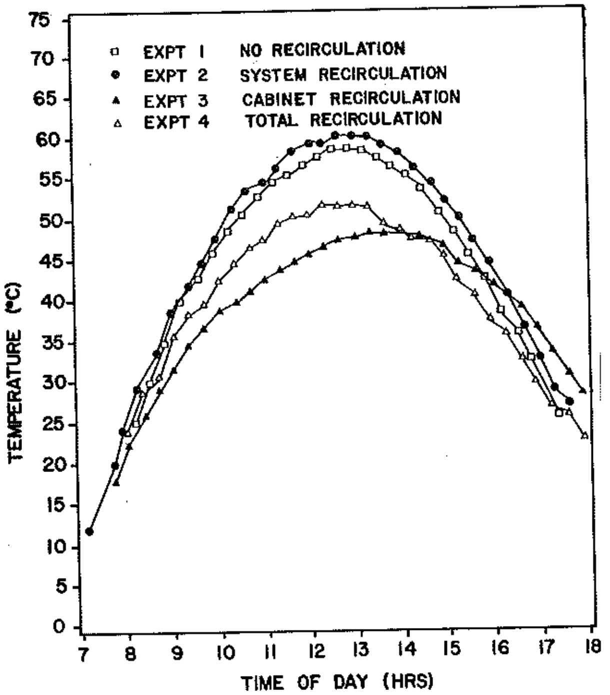

Fig. 5 Comparison of the T6 histories of experiments 1, 2, 3 and 4.

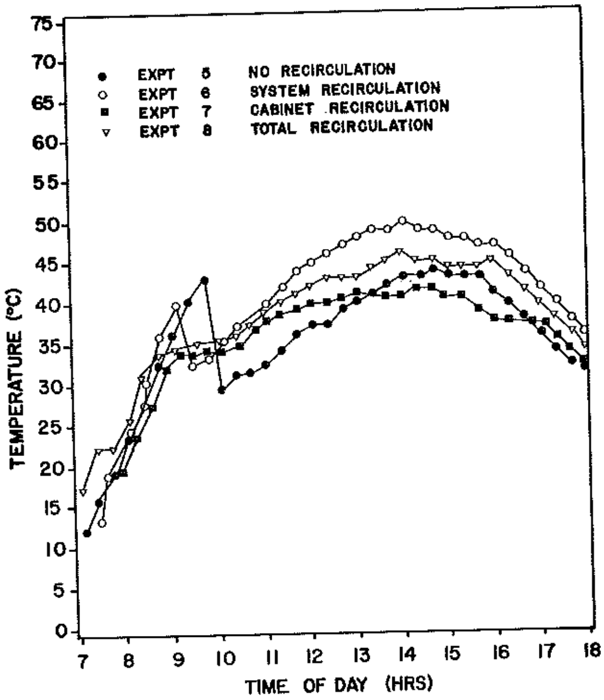

Fig. 6 Comparison of the T6 histories of experiments 5, 6, 7 and 8.

temperature throughout the apparatus as a manifestation of energy conservation resulting from system recirculation had been expected. The increase observed in T6 was therefore interpreted in this vein. A comparison between T1M to T7M values (Table 1) of experiments 1 and 3 and of 5 and 7 also supports the view that system recirculation conserved energy; the maximum temperatures attained during experiments 5 and 7 were consistently higher than the corresponding temperatures of experiments 1 and 3.

The intent of cabinet recirculation was to reduce the temperature stratification (i.e. the spatial variability) within the cabinet by recycling the air, through the fan housing, from the top to the bottom. Hence a decrease in the cabinet entrance temperature, T6, was not unexpected. As is illustrated in Fig. 7, in which the T1, T2, T6 and T7 histories of experiments 1 and 3 are compared, a concomitant increase in T7, which might reasonably have been expected, did not however occur. When cabinet recirculation was used, the difference between T6 and T7 was at most several degrees, but this was due mainly to a decrease in T6, whereas T7 remained almost the same. A similar pattern was found when the cabinet temperture histories of experiments 5 and 7 were compared. Evidently energy was lost from the recirculating air stream. Part of this loss may have been due to heat storage in the fan housing walls and partitions. At the end of the day, both T6 and T7 decreased less rapidly during experiment 3 than during 1. Some of the heat stored in the fan housing may have been recovered during this latter period. Heat may also have been transferred to other air streams, either by conduction through the walls or by convection through leaks. As shown in Fig. 7, during experiment 3, T2 was consistently higher than during experiment 1, although the T1 histories were very similar. This was also found true when the T1 and T2

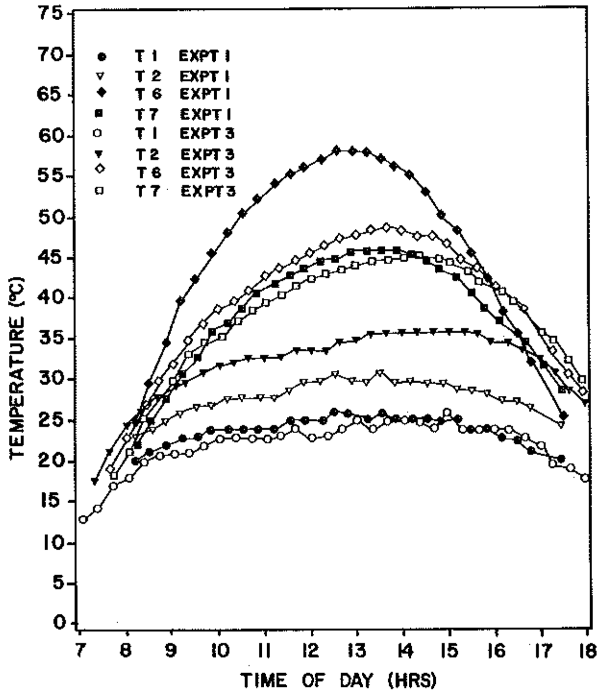

Fig. 7 Comparison of the T1, T2, T6 and T7 histories of experiments 1 and 3.

histories of experiments 5 and 7 were compared. Overall, the use of cabinet recirculation caused the conditions within the cabinet to be more uniform, albeit at the cost of a loss of energy available for drying. Cabinet recirculation also caused the temporal variability of cabinet temperatures to be reduced somewhat.

In Fig. 8, the T3, T6 and T7 histories of experiments 1 and 5 are compared. The only major difference between these was that during experiment 5 a sequence of operating modes was utilized, whereas during 1 only the straight-through mode was used; no recirculation was used in either. Considerably lower cabinet temperatures, T6 and T7, were attained during experiment 5 than during 1, but their temporal variability was also lessened. The heat storage mode was effective in limiting the maximum cabinet temperatures, and use of the heat recovery mode at the end of the day raised these temperatures somewhat. The spatial variability of the cabinet temperature was also reduced when the sequence of modes was used. This was probably due to the heat loss from the drier cabinet being lower during experiment 5 as a result of the cabinet temperature being lower. Patterns similar to those described above were found for the three other sets of corresponding experiments – 2 and 6, 3 and 7, and 4 and 8. Cabinet temperatures were lower when the sequence of modes was used but the cabinet temperature variability, both temporal and spatial, was reduced.

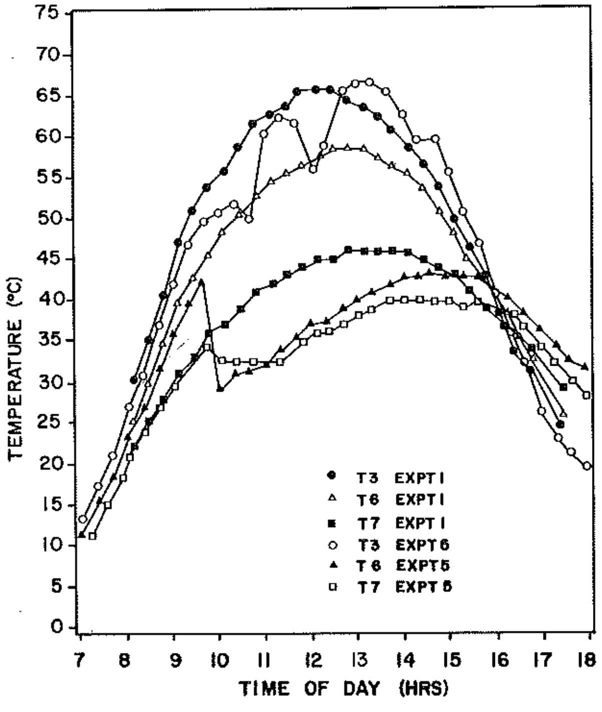

Fig. 8 Comparison of the T3, T6 and T7 histories of experiments 1 and 5.

The combined effects of the use of the sequence of modes together with both system and cabinet recirculation are illustrated by the results of experiment 8, which are shown in Fig. 9. As is evident from the T1 and T2 histories, the day was rather warm but variable, with several cloudy periods limiting the radiant energy input. T6 and T7 were however kept fairly constant between 9:00 and 16:00 h and within several degrees of one another. In this respect the performance of the drier under these conditions was a success. The cabinet temperatures attained during this period fluctuated between 30 and 45°C, which are somewhat lower than desirable. Also, not enough heat was available to extend the period of relatively steady cabinet temperature beyond the 16:00 h limit. Both these shortcomings were largely caused by the low level of radiant energy available during the Zambian winter.

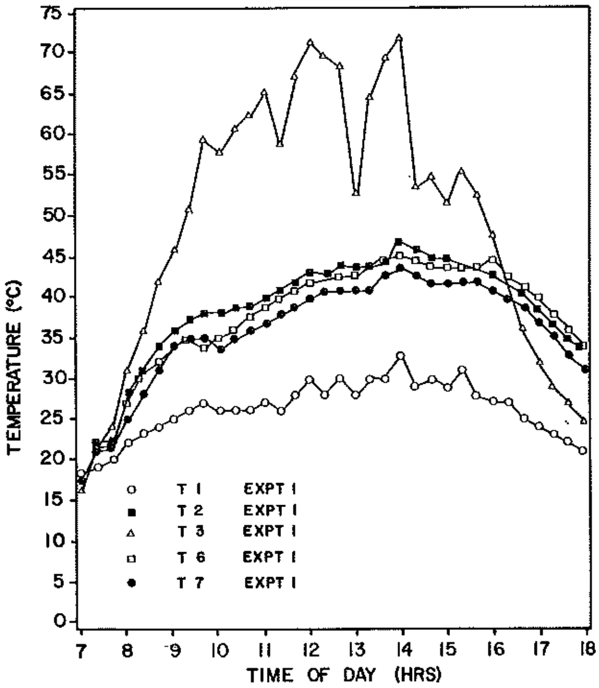

Fig. 9 The temperature histories obtained during experiment 8.

FOOD DRYING – METHODS AND RESULTS

The drying rates of various foods and the effects on these rates of the tray position and operating submode were evaluated in a set of eight experiments, numbered 9 to 16. Cabbage, okra and beef were dried. Cabbage and okra are staple foods in Zambia. Beef is by far the major animal protein source consumed there and is frequently sun-dried, especially in rural areas. Before being dried, cabbage was first washed with tap water and then cut into pieces approximately 2 X 2 cm. Okra was cut into slices 5 mm thick, but was not washed since wetting makes it difficult to handle. The beef was cut into 1 cm cubes. None of the foods were blanched before drying. Products were prepared in 5 kg lots and loaded at 500 gm per tray in the drier cabinet at the start of an experiment. The tray contents were occasionally re-spread in the course of the experiments. During all the experiments, except experiment 9, the order of the trays was from time to time randomly rearranged. After every 2 h of operation, a small sample (corresponding to about 5 g of raw food) was taken from each tray. For experiments 10 to 16 these were mixed to obtain a more or less representative average sample of the food in the drier. The moisture contents of the samples were determined by weighing before and after a 24 h drying period in an oven at 96°C. All moisture contents reported were calculated on a wet weight basis. Temperatures T1 to T7 were also recorded every 20 minutes during the active drying period, i.e. when the fans were on. Of necessity, only a very limited number of combinations of operating conditions and foods were investigated. The straight-through operating mode with various submodes was used for all experiments. Each experiment lasted two days. The food was loaded into the drier at 8:00 in the morning of the first day and the fans were started. They were then shut off at 5:00 that afternoon and the food left in the drier overnight. The second day the fans were again started and shut off at the same times.

Experiment 9 was carried out to study the effect of the tray position on the drying rate. Hence, the trays were not rearranged and the moisture content samples not combined. The trays were numbered from 1 to 10, starting at the bottom of the drier, nearest the air inlet. Cabbage was placed on the trays and the system recirculation submode was used. The cabbage moisture contents on trays 1, 4, 7 and 10 are shown in Fig. 10. It is obvious that the cabbage dried substantially faster in the bottom than in the top of the cabinet. This may have been due to the temperature spatial variability as well as to the fact that the air in the top of the cabinet had a higher moisture content than the air in the bottom. Time was not available to investigate this further. As a result of these observations, in all subsequent drying experiments the trays were occasionally rearranged so that they would, on the average, be exposed to similar conditions.

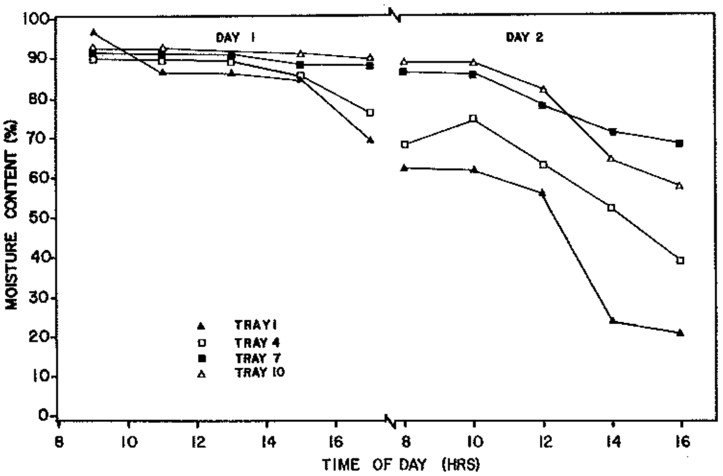

Fig. 10 Cabbage moisture contents on four trays.

In experiments 10 and 11, cabbage was dried. In the former experiment, system recirculation was used, whereas in the latter no recirculation was employed. The moisture content and T6 histories are shown in Fig. 11. During the total active drying periods of 18 h, the moisture content of cabbage was reduced from 92% to 36% and 46% respectively. The use of system recirculation resulted largely, as before, in higher T6 values. It also caused the cabbage to dry faster. Unusually high afternoon temperatures on day 2 of experiment 11 resulted in T6 values above the corres-

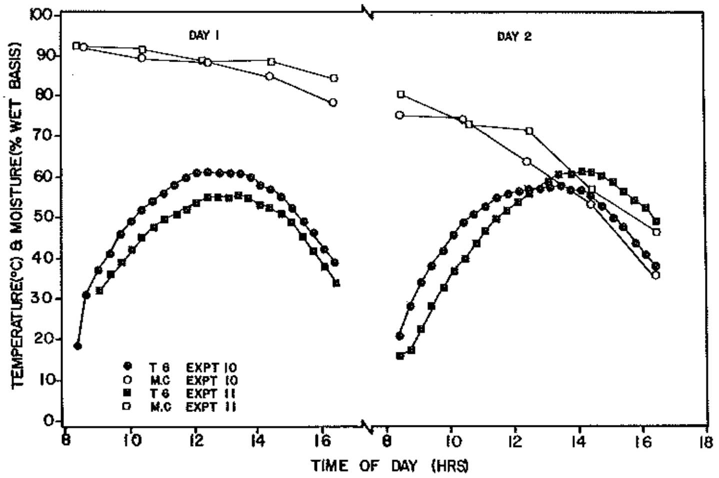

Fig. 11 Drier cabinet inlet temperatures and cabbage moisture contents obtained during experiments 10 and 11.

ponding ones of experiment 10. In neither experiment did the cabbage dry to a moisture content satisfactory for storage. A third day of drying would probably have decreased the moisture content adequately.

Okra was dried in experiments 12 and 13. System recirculation was employed in the former and no recirculation in the latter. The T6 and moisture content histories are shown in Fig. 12. The results are quite similar to those of experiments 10 and 11, except that the okra was dried to a more acceptable extent. In the two experiments moisture contents of 7% and 12% respectively were attained; the okra initial moisture content was 86%. The use of system recirculation again generally increased T6 as well as the drying rate.

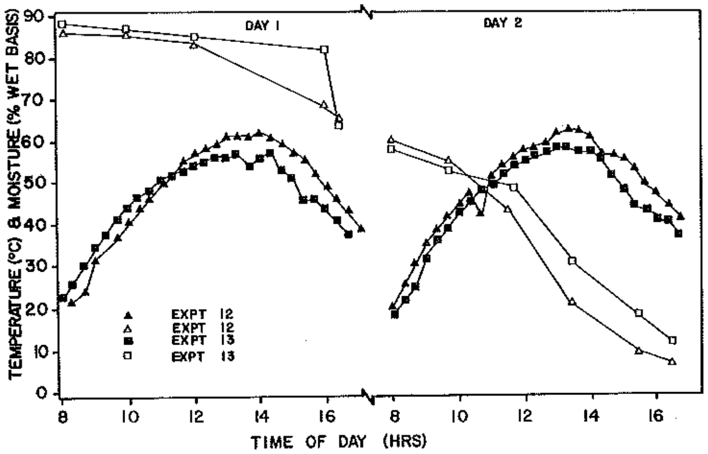

Fig. 12 Drier cabinet inlet temperatures and okra moisture contents obtained during experiments 12 and 13.

Three beef drying experiments, 14, 15 and 16, were carried out. System recirculation was used during 14 and 15, whereas cabinet recirculation was implemented during 16. The T6 and moisture content histories are shown in Fig. 13. The T6 values of experiments 14 and 15 were almost identical for day 1 but differed substantially in the afternoon of day 2. This was due to meteorological conditions. The T6 of experiment 16 was, as expected, generally somewhat lower than that of 14 and 15. The drying rate was initially higher for the two experiments during which system recirculation was used, but the final moisture contents obtained for all three were very similar, being 11%, 11% and 12% respectively.

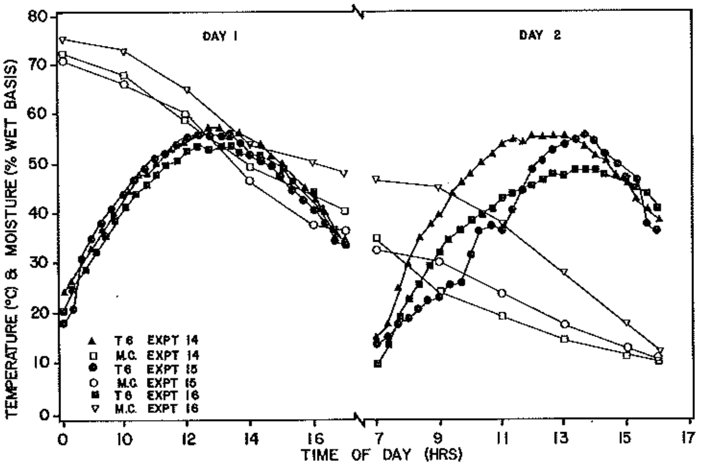

Fig. 13 Drier cabinet inlet temperatures and beef moisture contents obtained during experiments 14, 15 and 16.

ECONOMICS

A simple economic analysis of drier performance under Zambian conditions, in US currency values, is presented below. Although the actual cost incurred was considerably higher, it is estimated that the drier could be constructed for US$500. The authors paid a premium price for many materials and services because of time restrictions. Also, the design could be simplified somewhat and construction speeded up after some assembly experience. Every two days 5 kg of wet material can be dried. The cost of raw material per batch would be about US$5.00 (US$1.00/kg), and 0.85 kg product would result, having a value of US$12.75 (US$15.00/kg). About 4 h of labour is required per batch to cut the wet material, turn it on the screens, switch the fans on and off, manipulate the controls and collect and package the product. The labor cost is therefore about US$4.00/batch (US$1.00/h). In Zambia the cost of electricity to run the fans is practically negligible compared to the labor cost, but this may not be so elsewhere. On the basis of 200 days of operation per year, 100 batches could be processed annually. This would result in an income of US$1275/yr. If it is assumed that the US$500 capital equipment outlay for the drier is borrowed and is written off over 10 years, the interest rate is 10%, and the annual maintenance amounts to 10% of the capital equipment cost, the total annual capital cost is US$150 (US$1.50/batch). Therefore the profit would be US$225/yr (US$1275 sales – US$500 raw materials – US$400 salaries – US$150 capital costs) or US$2.25/batch.

In the above analysis the cost of selling is not included. The producer could generate a wage of US$400/yr from labor and a further US$225/yr from profits, but the process only occupies him

2 h/day. To be commercially viable a wider unit might be constructed – the design readily lends itself to this. If 25 kg wet material is processed per batch, the producer would have to work 8-10 h/day and would earn US$3125/yr.

CONCLUSIONS

A small-scale, forced convection, indirect solar food drier was designed, built and tested in Zambia. It consisted of a novel arrangement of five modules. The equipment was readily expandable, in that its width could simply be increased without any major design alterations being necessary. The materials and technology used in its construction were matched to Zambian conditions. The equipment is easy to copy and operate; it was built and run by Zambian personnel. Despite its simplicity, the equipment was very flexible, in that it could be operated in a number of modes and submodes. Heat storage and recovery modes were provided to reduce the temporal variability of the cabinet temperature; cabinet recirculation could be used to reduce its spatial variability. A system recirculation submode was provided primarily to conserve energy. The design objectives were met to a certain degree (e.g. in experiment 8 the simultaneous use of a sequence of operating modes and both submodes yielded fairly steady and unstratified, if somewhat low, cabinet temperatures).

Energy could probably be conserved better if the fan housing and control unit as well as the drier cabinet were insulated. This would reduce heat loss, increase temperatures, and reduce heat transfer between streams within the equipment. It would also be an improvement to have sufficient heat collection and storage capacity to allow continuous operation. Heat storage and recovery could then be used to full advantage and the conditions in the cabinet could be kept more stable. An integrated, rather than a modular, construction approach could be used for a commercial version of the equipment so that it might be built with less material so as to decrease the incidental thermal mass associated with it as well as the construction cost. This would probably increase the construction labor requirement and therefore the construction time. It is estimated that the cost of materials for a commercial drier of this type would amount to about 1000 Kwacha (US$1600).

From the food drying experiments performed, it was evident that a wide variety of foods could be dried in the equipment in two or three operating days. Some experimental work was also done with pumpkin leaf and roselle; those too were successfully dried in two days. The food quality as such was not determined by experimental means, but food texture, color and flavor were subjectively judged to be excellent compared to locally dried products. For an initial, experimental version, the drier, despite its limitations, performed adequately and served to prove that in principle a solar collector, a heat storage unit and a conventional tray drying cabinet can be combined into a very flexible unit of an appropriate technological level. From a simplified economic analysis it seems that this would be profitable.

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REFERENCES

Bolin, H.R., A.E. Stafford and C.C. Huxsoll (1978), Solar heated fruit dehydrator, *Solar Energy,* Vol. 20, pp. 289-291.

Cruess, W.L. (1948), *Commercial fruit and vegetable products,* 3rd ed., McGraw-Hill Book Company, pp. 475-508.

Garg, H.P., P.C. Pande and K.P. Thanvi (1978), Development of a solar agricultural drier, *Proc. of National Solar Energy Convention of SESI,* 20-22 Dec., pp. 286-290.

Ismailova, A.A. (1957), Possibility of applying solar energy to drying fruit and vegetables, *Teplo-energetica,* Vol. 1.

Kalra, S.K. and K.C. Bhardwaj (1981), Use of a simple solar dehydrator for drying fruit and vegetable products, *J. Food Sc. Tech.,* Vol. 18, pp. 23-26.

Khan, E.U. (1964), Practical devices for utilization of solar energy, *Solar Energy,* Vol. 8, No. 1, pp. 17-22.

Kwendakwema, N.J. (1983), *Solar food drying in Zambia,* M.Sc. thesis, McGill University, Montreal, Quebec, Canada.

Lawand, T.A. (1966), A solar cabinet drier, *Solar Energy,* Vol. 8 No. 1, pp. 158-164.

Szulmayer, W.L. (1978), From sun-drying to solar dehydration, *Food Technol. in Australia,* Vol. 23, pp. 440-443.

van Arsdel, W.B. (1973), Drying phenomena, *Food Dehydration,* Vol. 1, van Arsdel, W.B., A.I. Morgan and M. Coply eds., AVI Publishing Co., Westport, Conn., pp. 22-57.