# Development of Solar-Assisted Dryers for Food and Farm Crops

P. H. Hien, L. Q. Vinh, T. T. T. Thuy, T. V. Tuan

**Abstract.** *"Solar energy is free but not cheap." That thought has driven research at Nong-Lam University to design, fabricate, and test mechanical dryers of different capacities, using solar energy as the heat source, the aim being to reduce the drying costs due to fossil fuels. The dryers are based on the air reversal principle. The machine has three components: an axial-flow fan; a drying bin containing the agricultural material, wherein the airflow can be set upwards or downward; and a solar collector consisting of two parallel horizontal cylinders made from polyethylene (PE) transparent sheet. Work started with a laboratory dryer for 5 kg of material per batch, from which basic data on the solar collector were obtained. Next, a full-scale 500 kg macaroni dryer was designed, and drying tests showed that the solar collector could replace the coal furnace of an existing macaroni dryer, which had consumed 6 kg of coal per hour for drying a batch in 5 h. With solar radiation ranging from 500 to 900 W/m$^2$, the drying temperature reached 37°C to 52°C, averaging 14°C above ambient temperature. The collected power was 44 kW, and the collector efficiency was 40%. By substituting coal with solar energy, the macaroni dryer has saved US$120/month, or 100% of the fuel cost. Compared to its initial cost and the replacement cost for the PE tube every seven months, the payback period is less than one year. Use of clean solar energy meets the hygienic requirements for food drying. Drying tests in the 2007 dry-season harvest using a popular 4-ton paddy dryer with a solar collector showed that solar energy could contribute to a cost saving of 43% to 78% by reducing coal consumption, while maintaining the capacity and quality as normally practiced with conventional fuel.*

***Keywords.*** *Food drying, Macaroni, Rice, Solar collector, Solar drying.*

Mechanical drying is a better way than sun drying to ensure the hygienic requirements of food, to operate independently of rainy weather, and to save labor. However, mechanical dryers require fuels such as coal or oil, which entails high drying cost, and which is a factor impeding the acceptance of the machine itself.

Solar energy is an inexhaustible source of energy for drying, and several research studies have been published on solar drying. However, recalling the popular saying "solar energy is free but not cheap," while research on solar drying has resulted in numerous dryers, very few among these have brought economic profits on long-term operation at production scale (Foster and McKenzie, 1980; FAO, 1985; Muhlbauer and Esper, 1995; Sukhatme, 1996; Garg and Kumar, 2001; Kamaruddin, 2002). Results were usually achieved with dryer capacities in the range from a few kilograms of fruit to some hundred kilograms of paddy, although the investments were not small. Typical is a review by Exell (1993) of a million-dollar-scale solar rice dryer project: "The dryers were said to be too small." Thus, the key objective should be high capacity at reasonable cost. That thought has driven research at Nong-Lam University (NLU) in Ho Chi Minh City, Vietnam, towards new attempts with solar drying (Hien et al., 2007a, 2007b). The objectives were to design, fabricate, and test solar-assisted mechanical dryers of different capacities, with a wide range of products such as macaroni, paddy, water hyacinth, and ear mushroom, the aim being to reduce the drying costs due to fossil fuels.

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## Materials and Methods

Works started with a laboratory dryer for about 5 kg of material per batch. The data on the solar collector were used to design and fabricate a full-scale 500 kg macaroni dryer. Another dryer was designed for high-moisture products such as mushroom and water hyacinth. Next, a popular 4-ton paddy dryer was tested with solar energy. Standard textbooks (Duffie and Beckman, 1980; Sukhatme, 1996) were referred to for initial designs. For measuring the solar total irradiance, a Daystar solarimeter was used, with 3% accuracy at 1000 W/m$^2$ and 1 W/m$^2$ resolution. Temperatures were measured with different thermometers (mercury-in-glass and infrared) with 0.5°C accuracy. Simple statistical data analyses were made on replicated measurements.

### The Laboratory Dryer

Construction of the 5 kg laboratory dryer is shown in figure 1 (Hoang, 2005; Bich, 2006). The drying chamber consists of six 0.39 m × 0.39 m trays. A 12 W fan with an airflow of ~0.02 m$^3$/s draws heated air from the solar collector and blows it through the trays. The collector is a 3 m$^2$ polyethyl-

  


**Figure 1. The laboratory dryer: (1) solar collector, (2) suction fan, (3) air duct, (4) drying chamber, and (5) trays.**

ene tube, with black absorber inside. To estimate the heat power of the collector, comparison was made with a variable electric resistor that produced the same temperature increase under the same airflow and ambient temperature. Measurements were repeated on several days with different solar radiation levels.

### The Macaroni Dryer

Based on data obtained from the laboratory dryer, a 500 kg macaroni solar dryer was designed, tested, and applied by a food company in Ho Chi Minh City. The dryer is based on the air reversal principle (fig. 2), which has been applied widely for paddy drying in the Mekong Delta and Vietnam since 2001 (Hien et al., 2003). Advantages of air reversal drying include: saving of land space; mechanization, meaning less manual labor; and multi-crop use, including high-moisture products such as coffee, sliced cassava, and longan.

The dryer has three components: a two-stage axial-flow fan, a drying bin containing 500 kg of macaroni wherein the airflow can be set upwards or downward, and a solar collector. The collector consists of two parallel 1 m diameter, 25 m long horizontal cylinders, made from heavy polyethylene (PE) transparent sheet, with black PE sheet inside as heat absorbers (fig. 3). In this case, the solar collector replaces the coal furnace of an existing macaroni dryer, which had consumed 6 kg of coal per hour for a drying a batch in 5 h.

Drying tests were conducted while ambient conditions, including solar radiation, were recorded every 15 min. Ten samples, each with 500 g of macaroni enclosed in nylon-net bags, were embedded in the drying mass (five at the top and five at the bottom) and weighted every hour. When drying stopped, the final moisture content (MC) of the samples was measured by the oven method, from which the initial MC could be derived.

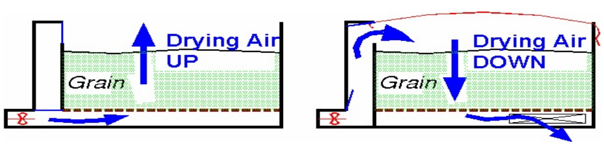


**Figure 2. Principle of air reversal drying.**


**Figure 3. The macaroni dryer.**

### The Paddy Dryer

In the Mekong Delta of Vietnam, farmers use flat-bed dryers for paddy. Currently, there are about 6000 units (capacity 4 to 12 tons per batch), which are used mostly for paddy harvested in the wet season. For the dry-season harvest, farmers mainly rely on natural sun drying on pavement to save the cost of fuel. Thus, paddy crack in the dry-season harvest is even more severe, meaning lower head rice recovery (as repeatedly warned by research and extension agencies without much result, due to the very low drying cost under sunshine).

Thus, the idea of using solar energy was adapted for the dry-season paddy. A popular, 4-ton air-reversal flat-bed dryer (model SRA-4B) fabricated by a local mechanical shop was selected. This is a collapsible unit and consists of the following components:

- Two-stage axial fan, powered by a 15 hp Chinese diesel engine.
- Coal furnace, with coal consumption adjustable within 5 to 12 kg/h.
- Drying bin, with a 4.50 m × 3.27 m grain floor made from bamboo slat and nylon net. The bin is supported by seven metal legs and thus can be easily installed on rough land. The airflow can be upwards (fig. 4) or downward (fig. 5) with a covering tarpaulin.
- Solar collector, designed at the NLU Center for Agricultural Energy and Machinery, consisting of two cylindrical plastic collectors (figs. 4 and 5). Each cylinder is 1.0 m in diameter and 27 m long. Inside the transparent plastic layer is a black PE layer for absorbing heat. The two cylinders converge into a transition box, which also received heat from the coal furnace.

The collector used inexpensive materials such as bamboo slats and plastic cords, and was installed on open ground instead on a rooftop. Thus, the investment cost was significantly reduced compared to the steel-frame collector used for


**Figure 4. SRA-4B dryer with upward airflow.**


**Figure 5. SRA-4B dryer with downward airflow, using solar heat.**

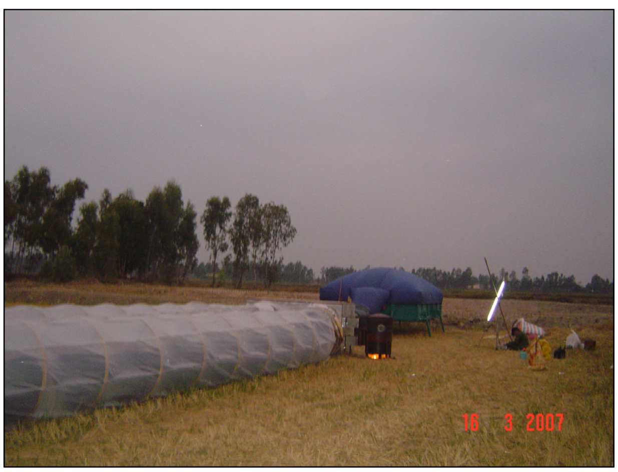


**Figure 6. At sunset, the coal furnace is fired.**

the macaroni dryer. The solar collector and the coal furnace can be used separately or in combination (fig. 6).

Tests were done at Long-An Province in March 2007, the driest month of the year. The MC was measured every hour by a Korean-made GMK-303RS MC meter, which had been calibrated against the drying oven. The airflow was obtained by multiplying the drying bed area by the average superficial velocity, measured by a rotameter at 30 points over the drying bed. The rotameter had been calibrated by the orifice method (Ower and Pankhurst, 1997).

The contribution of solar energy was examined by two calculations. One calculation used the index product ($I_p$, °C·h), which is the product of the temperature increase and the corresponding heating time. The $I_p$ using solar energy was compared to the total $I_p$ using both coal and solar energy; the ratio indicated the share of solar heat. The second calculation considered the percentage saving of coal due to solar energy, compared to the case in which only coal was used without solar heat. Table 1 in the Results and Discussion section illustrates these calculations.

## Results and Discussion

### The Laboratory Dryer

Figure 7 shows the heat power of the 3 $m^2$ solar collector of the laboratory dryer, which ranged from 300 to 1200 W, corresponding to an temperature increase of 6°C to 22°C, which is the difference between drying and ambient temperature. The drying temperature reached 36°C to 50°C. This is the basic data used in up-scaling the collector with the same configuration. The laboratory dryer was tested with different available materials, loaded on the same six trays, to confirm the above heat power. For example, 4.1 kg of fish with an initial MC of 69.6% was dried down to 19.7% MC in 21 h (two sunny days).

### The Macaroni Dryer

Drying tests in March 2006 with solar radiation ranging from 500 to 900 W/$m^2$ (average 680 W/$m^2$) showed that the drying temperature reached 37°C to 52°C, averaging 14°C above ambient temperature, over 5 h drying time (fig. 8) in the 500 kg macaroni dryer. The moisture content reduction of a typical drying batch is shown in figure 9. The collector power was estimated from the drying temperature, the airflow, and the coal consumption of a batch under similar conditions. The collector power was about 44 kW, and the collector efficiency was 40%. During the rainy days of April to June 2006, drying from solar energy alone was confirmed, although the drying time stretched out to 6 to 8 h.

The economic return of the macaroni dryer has been monitored in actual production since February 2006. By substituting coal with solar energy, the collector has saved US$120/month, or 100% of the fuel (coal) cost. Compared to the initial cost of US$900 and the US$50 replacement cost for the PE tube every seven months; the pay-back period is less than one year. Use of clean solar energy meets the hygienic requirements for food drying.

### The Paddy Dryer

Five drying batches were tested in March 2007 in the paddy dryer: batch 1 with heat from coal only, batches 2 and

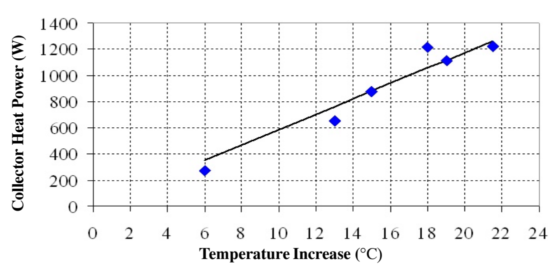


**Figure 7. Collector heat power as a function of the temperature increase (ambient air temperature = 29°C to 32°C, RH = 80% to 90%).**

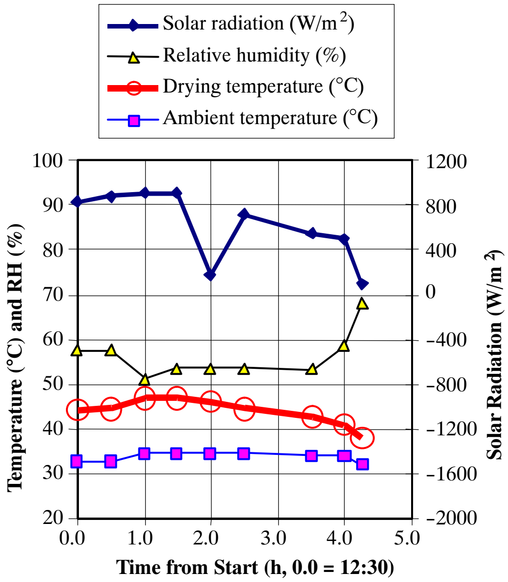


**Figure 8. Ambient conditions and drying temperature for the drying batch on 8 February 2006 (initial MC = 39.8% w.b.).**

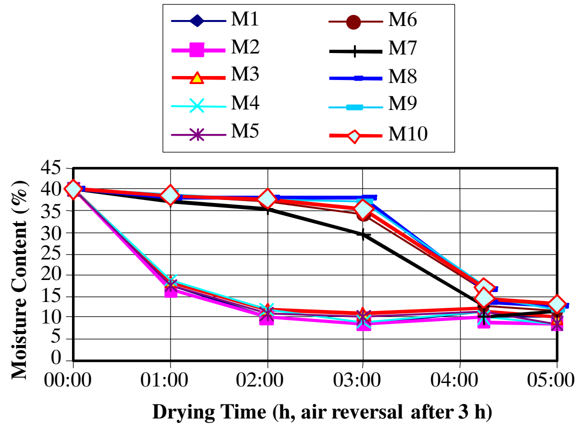


**Figure 9. Moisture content reduction of the drying batch with solar heat (batch 3, 8 Feb. 2006, initial MC = 39.8% w.b.): M1 to M5 = samples at bottom layer; M6 to M10 = samples at top layer.**

3 with heat from solar energy only (fig. 9), and batches 4 and 5 with heat from both coal and solar energy. The results are summarized as follows:

- The capacity was 3.8 to 4.1 tons per batch of 7 to 12 h, with moisture reduction from 23.8% ±1.7% to 14.2% ±0.8% (average ±standard deviation).
- The drying temperature could be adjusted within 38°C to 44°C using coal. With solar heat, the drying temperature could reach 38°C with good sunshine (over 800 W/m$^2$ radiation) or only 36°C in cloudy weather (about 500 W/m$^2$ radiation, which is also typical in wet seasons). With less sunshine, the 12 h drying time, as in batch 3, was expected.
- The combination of solar and coal heat is useful for ensuring that a batch is dried within one day. The harvest season in one location (village or commune) usually lasts less than 25 days and thus does not allow the "luxury" of a two-day drying.
- The head rice recovery in all batches was comparable to "shade" drying, and thus quality was ensured.

The contribution of solar energy is analyzed in table 1, using data from batches 4 and 5. The following conclusions can be drawn:

- Solar energy could contribute to a cost saving of 43% to 78% by reducing coal consumption. This saving

**Table 1. Contribution of solar energy in combined mode (coal and solar).[a]**

| | | Batch 4 | Batch 5 |
|---|---|---|---|
| **Share of solar heat** | | | |
| Total drying time (solar + coal) (h) | $t_{total}$ | 7.50 | *6.92* |
| Drying time with solar heat (h) | $t_{solar}$ | 5.83 | 3.00 |
| Drying temperature (°C) | -- | 39.7 | 41.3 |
| Ambient temperature (°C) | -- | 32.6 | 33.5 |
| ==> Temperature increase (°C) | $\Delta T_{solar}$ | 7.1 | 7.8 |
| Index product, $I_{ps}$ (°C·h) | $I_{ps} = \Delta T_{solar} \times t_{solar}$ | 41.33 | 23.55 |
| Drying time with coal heat (h) | $t_{coal}$ | 1.67 | 3.92 |
| Drying temperature (°C) | -- | 37.6 | 38.2 |
| Ambient temperature (°C) | -- | 31.4 | 28.8 |
| ==> Temperature increase (°C) | $\Delta T_{coal}$ | 6.3 | 9.3 |
| Index product, $I_{pc}$ (°C·h) | $I_{pc} = \Delta T_{coal} \times t_{coal}$ | 10.44 | 36.61 |
| Thus: Share of solar heat (%) | $I_{ps} / (I_{ps} + I_{pc}) \times 100$ | 79.8 | 39.1 |
| Share of coal heat (%) | $I_{pc} / (I_{ps} + I_{pc}) \times 100$ | 20.2 | 60.9 |
| **Percentage saving of coal due to solar energy** | | | |
| Coal consumption (kg/h) | $C_c$ | 6.41 | 6.94 |
| Actual coal consumption with solar heat (kg) | $C_c \times t_{coal} = C_{withSolar}$ | 10.7 | 27.2 |
| Total coal consumption with coal only (kg) | $C_{allCoal}$ | 48.1 | 48.0 |
| Thus: Coal saving (kg/batch) | $C_{allCoal}$ - $C_{Solar}$ | 37.4 | 20.8 |
| Cost saving with coal @ US$0.137/kg (US$/batch) | -- | 2.9 | 5.1 |
| Quantity of paddy dried (kg) | -- | 3820 | 3880 |
| Coal cost per ton of paddy with solar heat (US$) | -- | 0.39 | 0.96 |
| Coal cost per ton of paddy with coal only (US$) | -- | 1.73 | 1.70 |
| Thus, the percentage saving of coal due to solar energy (%) | -- | 77.7 | 43.4 |

[a] Cost data are converted from 16,000 VND = US$1 (in 2006).

translates into a monetary value of US$2.9 to US$5.1 per batch, or US$0.74 to US$1.25 per ton (converted from US$1= 16,000 VND).

- For estimation, assume that in one year, the dryer is used for 100 batches, or 400 tons, of which half use exclusively solar energy and half use supplementary solar energy with 50% saving, or US$1.6 and US$0.8 per ton, respectively. Thus, the total saving is US$480 per year.
- Compared to the additional investment for the solar collector of about US$560, with the replacement of the plastic sheet costing about US$120 after every seven months, the payback period is about two years.
- A stand-alone dryer owner might not be able to dry 100 batches per year. In contrast, a dryer owner and rice miller could surpass that quantity easily. Thus, the solar collector would be more practical for a rice milling operation.

### Further Research on Solar-Assisted Drying

Drying of high-moisture products such as wood-ear mushroom and water hyacinth is currently under study with promising results. Wood-ear mushroom production has increased in recent years in various provinces, but farmers are reluctant to dry it due to the high cost of fuel required for removing a large quantity of water, i.e., removal of 6 kg $H_2O$ to obtain 1 kg of product. Dried water hyacinth has recently found use as a material for making handicraft products for export, but drying the plant with about 92% initial MC requires a large amount of energy, leading to excessive cost. Solar energy offers an alternative drying method that can reduce drying costs. In addition, a simulation model has been developed and verified, as part of an MSc thesis at NLU, and will be the topic of a future paper.

## Conclusions

Using basic test data from a laboratory-scale dryer, a 500 kg macaroni dryer using solar energy as the heat source was designed and tested at Nong-Lam University, Ho Chi Minh City, and proved to be economical over more than one year of operation at production scale. The collector power was 44 kW, its efficiency was 40%, and it replaced a 6 kg per hour coal furnace with solar heat. Basic data on configurations for the cylindrical solar collector were gathered from tests. Next, a popular 4-ton reversible paddy dryer in the Mekong Delta was augmented with a new design of cylindrical solar collector, and tests in the dry-season harvest showed that solar energy could contribute to a cost saving of 43% to 78% by reducing coal consumption. Promising prospects are apparent for application in drying other agricultural products.

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