

Development of Rice-husk Furnaces for Grain Drying

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Abstract

Two types of rice husk furnaces have been developed at the University of Agriculture and Forestry, Ho-Chi-Minh City, Vietnam. Both have a lower and an upper combustion chamber. The lower chamber is for burning charred husk and discharging ash. The upper cylindrical chamber is for trapping ash and burning volatile matter.

The first type has an inclined step-grate in the lower chamber. Rice husk consumption and drying air efficiency are 20–25 kg/hr and 70–75%, respectively. No ash or sparks escape from the furnace exit. From 1994 these furnaces have been used in many flat-bed paddy dryers (4 t/6 hour batch) in the Mekong Delta of Vietnam.

The second type has a vortex-type combustion chamber and no grate. Control of husk feed rate and the drying air temperature are automatic by a simple vibrating mechanism. The furnace was used in 1994 with an in-store dryer (80 t/4 day batch) installed at Song Hau Farm in the Mekong Delta. Rice husk consumption and drying air efficiency were 10–12 kg/hour and 70–84%, respectively. Drying air temperature (29–30°C) was controlled within $\pm 1^\circ\text{C}$.

Both furnaces are stable and simple to operate. They meet the requirement for low drying cost by the use of rice husk in the Mekong Delta.

ABOUT 2.5 Mt of rice husks are produced per year in the Mekong Delta, Vietnam. They have been widely used as a heat source for paddy drying since 1990. Current furnaces are box-type with an inclined grate (Fig. 1). They are built by farmers who adopted a prototype of the University of Agriculture and Forestry (UAF), Ho-Chi-Minh City in 1983. The UAF furnace was patterned after designs of Russian furnaces and an International Rice Research Institute (IRRI) rice-husk furnace. Box-type furnaces are simple and low cost. However, their disadvantage is that a great deal of ash and sparks is produced and sucked into the drying chamber. Also, in its current form it is difficult to improve its thermal efficiency.

UAF is applying in-store drying technology in Vietnam. This requires a furnace capable of long-term, continuous operation, stable temperature, and minimum labour requirement. Thus, a furnace with an inclined grate and a cylindrical combustion cham-

ber, and one with a pneumatic feed system, have been developed by UAF in order to meet the objectives of:

- trapping ash and sparks more thoroughly;
- improving furnace efficiency; and
- incorporating a device to automatically control the combustion rate and drying temperature.

Materials and Methods

Design of furnaces

Furnace with inclined grate and cylindrical combustion chamber (IGC)

An IGC furnace was designed in 1994 (Fig. 2). The lower part is box-shaped, built from fire bricks, and has an inclined steel grate. The upper part (patent pending) consists of two metal concentric cylinders, with the thicknesses of the inner and outer cylinders 5 and 1 mm, respectively. The gap between the two cylinders is filled with ash. A pipe located in the centre of the cylinders is connected to the furnace exit. Rice husks flow down from the hopper and along the

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surface of the grate by gravity and vibration forces which were transmitted from the dryer fan to the hopper via a cable. The dryer fan sucks primary air through the grate to burn the charred husk. Secondary air is extracted from the dryer fan to create a vortex in the cylinder to precipitate ashes and sparks, and burn the volatile matter.

Pneumatic-fed furnace (PNF)

A PNF furnace was developed in 1995 (Figs 3 and 4). It has two main components: a combustion chamber and a rice-husk feeding system. The combustion chamber is built from metal sheet and has two parts—upper and lower—which have the same functions as described for the previous furnace.

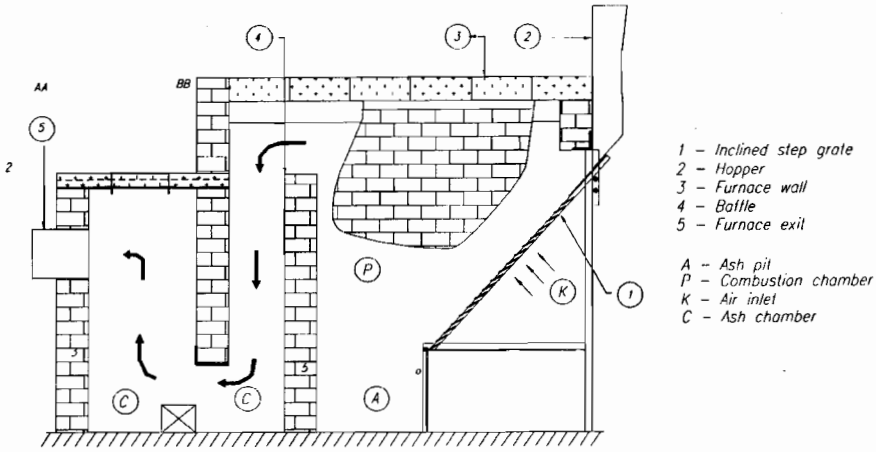


Figure 1. Box-type grate furnace

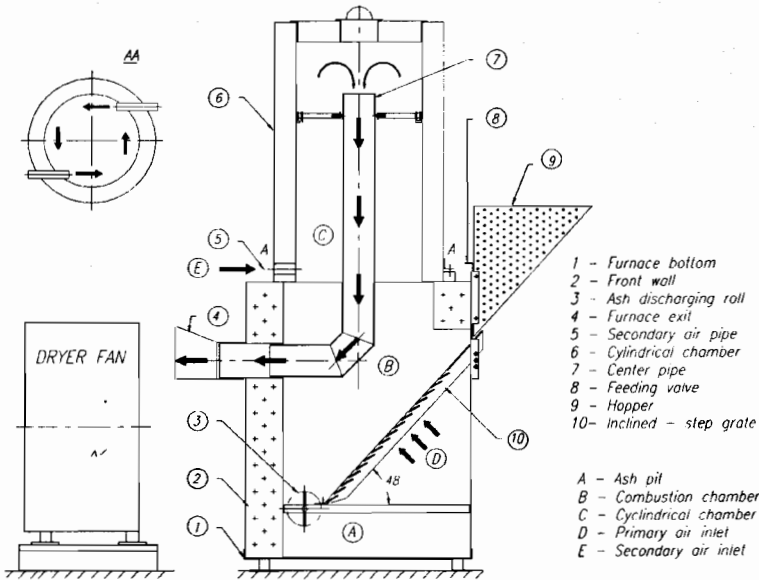


Figure 2. Furnace with Inclined Grate and Cylindrical combustion chamber (IGC)

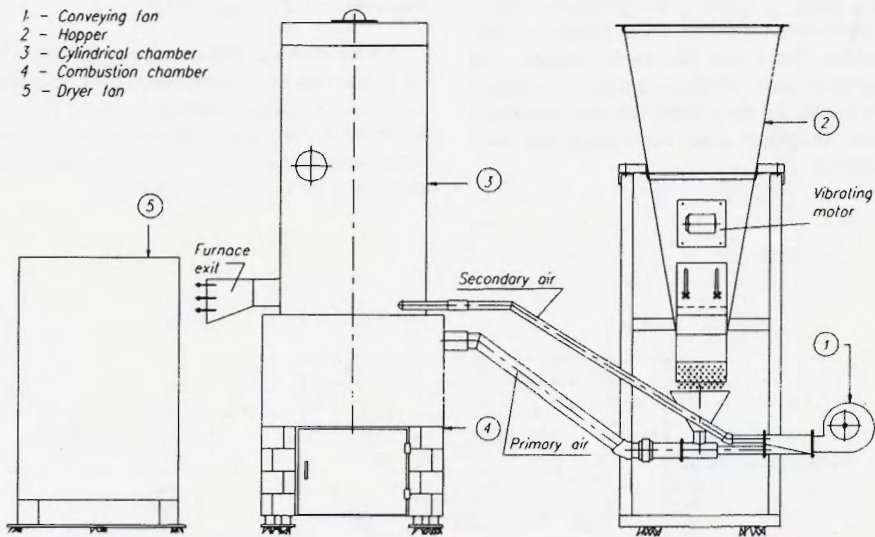


Figure 3. Pneumatic-Fed furnace (PNF)



Figure 4. Pneumatic-Fed furnace (PNF) at Song-Hau Farm, 1995.

The rice-husk feeding system consists of a vibrating hopper and a pneumatic conveyer which is patterned after a design published by the NRI (Natural Resources Institute, U.K.; Tariq and Lipscombe 1992; Robinson et al. 1993). Rice husks from the hopper flow down to the entry of the pneumatic conveyer, assisted by a vibrating motor. Together with the primary air, husks are forced tangentially to the lower part of the combustion chamber and form a

vortex. Rice husks are burnt as they fall to the bottom of the chamber. Secondary air is extracted from a conveying fan to create another vortex in the upper part of the chamber to precipitate ashes and sparks and burn volatile matter. The rice-husk feeding rate is controlled automatically by means of a thermostat which switches the vibrating motor on or off when the drying air temperature differs from the set value.

Instrumentation

A test duct 6 m long × 0.6 m diameter (Fig. 5) was used to simulate the dryer plenum so as to evaluate the characteristics of the furnace. Construction of the duct and setting of pressure and temperature measurement of air in the duct were adopted from the Japanese Industrial Standard code JIS B 8330-1962 (JMTI 1968). Air pressure was measured by pitot tube and digital manometer. A K-type thermocouple was used for measuring the ambient and drying air temperatures, and a shielded K-type thermocouple for measuring combustion chamber temperature. Temperature data were recorded by data logger. The CO₂ composition of the gas at the furnace exit was measured using Baccharach equipment. The primary and secondary air of the continuous furnace was determined by the orifice plate method (MacMillan 1992). This test was conducted to fix the position of the entry valve of the conveying fan.

Efficiency tests

Tests were conducted at three rice-husk feeding rates: 8, 10, and 12 kg/hour. During furnace operation, static and dynamic pressures and drying air temperatures were measured from the test duct, while the composition (e.g. %CO₂) of the gas produced was measured at the furnace exit. Combustion chamber temperature measurement was taken at the centre of the cylinder and 60 cm above the furnace bottom. Samples of about 250 g of ash were collected after each experiment, and sent to the Service Center of Laboratory Analysis of Ho-Chi-Minh City for determination of unburnt carbon (%U_c). The furnace efficiency (E_{ff}), the drying air efficiency (E_{ffdry}), and the excess air co-efficiency (%X_e) were determined using following equations:

$$E_{ff} = \frac{24.5}{\%CO_2} (T_c - T_a) / Lhv \tag{1}$$

$$E_{ffdry} = \frac{M_{air} * C_p (T_d - T_a)}{M_f * Lhv} \tag{2}$$

$$\%CO_2 = \frac{100 - \%U_c}{4.85102 - 0.01 * \%U_c + 0.048752 * \%X_e} \tag{3}$$

- where T_c = combustion chamber temperature, °C
- T_a = ambient temperature, °C
- L_{h_v} = average heat value of rice husk, kcal/kg
- M_{air} = airflow rate of dryer fan, kg/s
- C_p = specific heat of dry air, kcal/kg
- T_d = hot air temperature in test duct, °C
- M_f = rice husk consumption rate, kg/s.

Equation 1 is derived from heat balance of rice husk furnace (INPC1986), and equation 3 from a combustion equation for rice husks (Phan Hieu Hien 1992). Proximate and ultimate analyses of rice husk were obtained from the literature (Beagle 1978; Tiangco and Lipscombe 1992).

Drying tests

The IGC furnace was tested as a heat source for a 4 t flat-bed paddy dryer. Tests were conducted at Long-An Province in the Mekong Delta. Other tests of box-type furnaces were carried out in Soc-Trang and Can-Tho provinces. The PNF furnace was used for an 80 t in-store dryer at Song Hau Farm, Can-Tho Province, also in the Mekong Delta. The data were used to evaluate practical performance indicators such as drying air efficiency, stability, labour requirement, drying cost, etc.

Results and Discussion

IGC furnace

Experiment with test duct.

Figure 6 shows the temperature difference between the air temperature in the duct and ambient temperature with respect to time. After 2 hours of operation, the temperature difference was stable at about 12°C. Average airflow rate was 4.37 m³/s at a static pressure of 220 Pa in the duct. Furnace efficiency was about 70%.

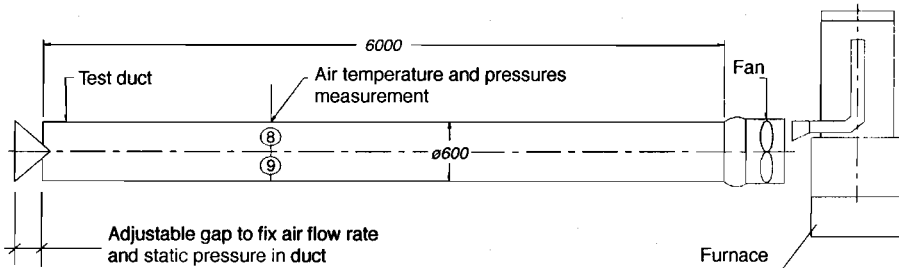


Figure 5. Fan test duct.

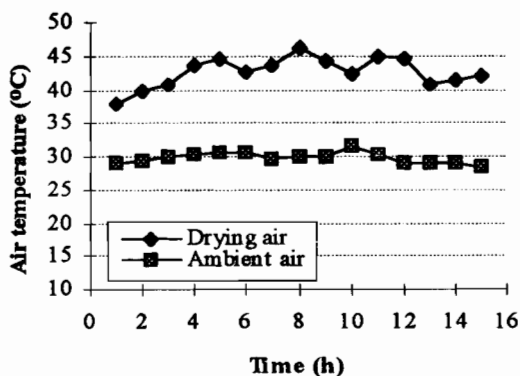


Figure 6. Drying air temperature of IGC furnace test

Experiment with flat-bed dryer

The batch of 4 t of paddy was dried from 26% moisture content (wet basis) to 14% in 6 hours. The rice husk consumption rate was 25 kg/hour with an average drying air temperature of 42°C. No ash or sparks were observed in the plenum. Ash was discharged manually every 20 minutes. Drying air efficiency was in the range 70–75% (Table 1).

Box-type furnaces

Table 1 shows the results of two box-type furnaces coupled to farmers' flat-bed dryers. The drying air efficiency was 41–65%. These results are noted here solely to illustrate the performance of most farmers' furnaces in the Mekong Delta.

PNF furnace

Efficiency tests

Rice-husk feeding rates of 8, 10, and 12 kg/hour were used. Results from experiments showed that the furnace operation was stable in the wide range of excess air coefficient ($X_e = 50\text{--}200\%$). The following quadratic functions show the relationships of the combustion chamber temperature (T_c), carbon conversion efficiency (C_{ce}) and furnace efficiency (E_{ff}) to the excess air coefficient.

$$T_c = 728.94 + 0.5169 X_e - 0.006990 X_e^2 \quad R^2 = 0.98$$

$$C_{ce} = 72.46 + 0.2122 X_e - 0.000522 X_e^2 \quad R^2 = 0.96$$

$$E_{ff} = 37.78 + 0.4270 X_e - 0.001268 X_e^2 \quad R^2 = 0.96$$

Maximum furnace efficiency was 75% at a rice-husk feeding rate of 10 kg/hour and an excess air coefficient of 160% (Figs 7–9).

Drying tests

In the experiments with an 80 t in-store dryer, a drying air efficiency of 84% was obtained. Drying air temperature fluctuated in a narrow range as shown in Figures 10 and 11. Average drying air temperatures were 28.3°C for recording interval 20 minutes, and 28.9°C for a recording interval of 2 minutes. Husk feeding and ash discharging were manual, at 2 hour intervals. Average ambient temperature was 22.8°C. Maximum deviation of the ambient temperature during the experiment was 4°C. The hot flue gas was clean in terms of ashes and sparks.

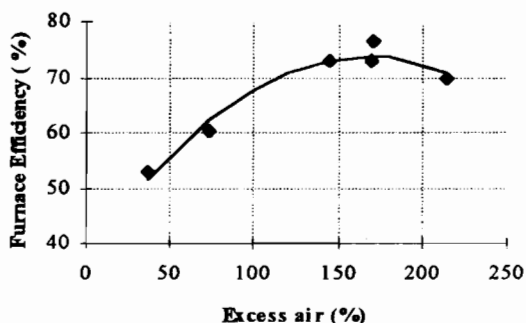


Figure 7. Effect of excess air on furnace efficiency of PNF furnace.

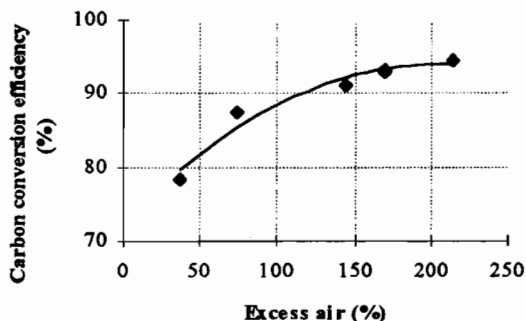


Figure 8. Effect of excess air on carbon conversion efficiency of PNF furnace.

Table 1. Results from drying tests of flat bed dryers with paddy in the Mekong Delta.

| Dryers | Bin size (m) | T_a (°C) | T_d (°C) | Airflow(m ³ /s) | E_{ffdry} | Flue gas |
|-----------|--------------|------------|------------|----------------------------|-------------|-------------|
| PhungHiep | 4 × 8 | 29 | 48 | 3.04 | 40.8 | ash & spark |
| Dai-Tam | 4 × 9 | 26 | 32 | 4.68 | 64.5 | ash & spark |
| UAF | 4 × 8 | 29 | 41 | 4.37 | 72.0 | clean |

Note: T_a = ambient temperature; T_d = drying air temperature.

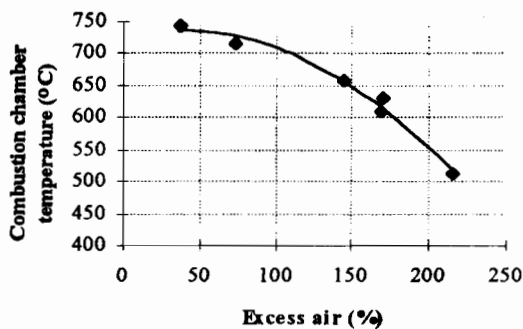


Figure 9. Effect of excess air on combustion chamber temperature of PNF furnace

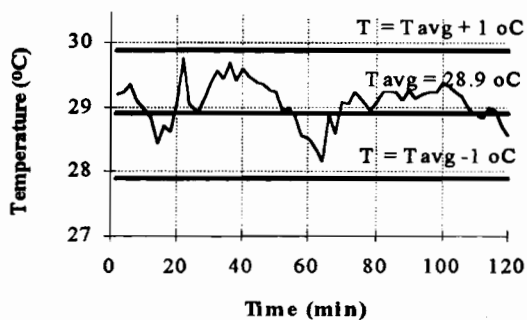


Figure 11. Air temperature in the plenum of in-store dryer (recording interval = 2 minutes) (PNF furnace)

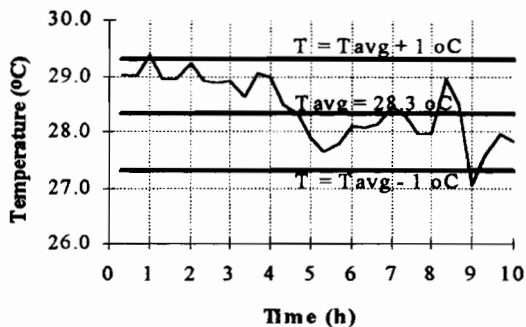


Figure 10. Air temperature in the plenum of in-store dryer (recording interval = 20 minutes) (PNF furnace)

Conclusion

The cylindrical chamber with a central pipe created a vortex resulting in cleaner flue gas and improved thermal efficiency of the furnace. The IGC furnace is now preferred by farmers for flat-bed dryers in the Mekong Delta. The PNF furnace, with its stable operation and automatic control of drying air temperature, is suited to a continuous operation system, such as in-store dryer or fluidised-bed dryer.

The construction of both furnaces is simple and they can be built by local medium-size workshops. They meet the requirement for low drying cost by the use of rice husk in the Mekong Delta.

Acknowledgments

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Pilot and Commercial Application of Ambient Temperature In-store Drying of Paddy in Northern Thailand

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FORCED aeration of bulk grain has become an increasingly popular practice over the last 10 years for a variety of reasons. Not only is it beneficial for keeping grain cool during storage to better maintain quality, it can also be used for slow drying which increases head yield of rice following milling, compared with traditional sun drying or rapid drying using hot air. Furthermore, aeration reduces the likelihood of insect infestation.

There now appears to be adequate definitive research to be able to assess the value of ambient temperature aeration of paddy rice in particular, compared with other methods of drying. Soponronnarit et al. (1994) have provided four-quadrant graphs relating initial grain moisture (%), depth of grain, airflow rate, drying time, and energy use for both paddy and maize. Other workers have developed similar models, and computerised simulation of drying for a number of variables (Driscoll 1987).

Despite this definitive work, the application of this technology in industry in Thailand has been slow and restricted to a few demonstrations close to Bangkok.

Areas far north of Bangkok face lower temperatures and, in many cases, higher relative humidity. Average temperature at Uttaradit in August–September is 0.5–1.0°C cooler than Bangkok, and average relative humidity is about 5% higher over the same months. So there was some concern that the technique of ambient temperature aeration may not be as successful for paddy drying in the wet season as it is at more southerly locations.

The Thai–Australian Agricultural Project, which had been assisting a large farmer group at Tron in Uttaradit Province establish facilities at a central grain market centre, conducted a small demonstration of aeration drying in the 1994 wet season. This was

done in one 50 t bay of a raised floor concrete store. In 1995, farmers and traders at the centre decided to build a new 300 t store suited to bulk handling and to incorporate in-store aeration.

Materials and Methods

In 1994, 600 mm wide semi-circular, corrugated ducting was used in a 6 × 6 m compartment of a 100 t concrete store. Ducts were 2 m apart and supplied by a backward curving centrifugal fan delivering 3.15 m³ air/sec (specific airflow of 1.9 m³/min/m³ of paddy). Only one batch of grain was tested, as the facilities were not completed until near the end of the wet season harvest. The test was carried out on 54 t of paddy of initial moisture content 20.9%. The depth of the grain bed was 3.5 m. A comparable batch of paddy was sun dried on a concrete pad to 14.7% moisture content and stored in the other compartment of the concrete store. Grain moisture levels were monitored at the top of the stack only, at regular intervals during the drying/storage period, using a standard Kett moisture meter. Temperature of the grain mass was monitored continuously using thermocouples linked to a Delta-T data logger. Paddy samples were taken at the beginning and end of the storage period and analysed for head yield, moisture content, and grain yellowing.

In 1995 the new store was constructed and the aeration system installed. The store consists of three open-fronted bays each 15 m long and 4.8 m wide. Each bay has two in-floor air ducts, 2.25 m apart and 1.25 m from each wall. The ducts are 50 cm wide, while the duct plenum chambers are 40 × 40 cm at the fan end, tapering to 40 × 20 cm at the store entrance end. The ducts are fed by two 5.5 kW backward curving centrifugal fans, each supplying 3.15 m³ air/sec. By means of a series of valves in the ducting manifold and the ducts themselves, six different airflow rates can be used, ranging from 0.3 to 3.8 m³/min/m³ of grain, assuming a full storage depth of 3.5 m.

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Thus, the system is very flexible, allowing for very low airflow rates for aeration cooling, through to the higher airflow rates required for grains such as maize, higher moisture grain, shallower depths of grain, or when storage time becomes more important than minimising specific energy consumption.

Thermocouples were installed temporarily in the rear of one bay only, to monitor temperature during the first drying cycle. Relative humidity and ambient temperature were also continuously recorded on a Delta-T logger.

To guide the operation of the aeration/storage system, a series of simulation drying runs was carried out using the computer program developed by the University of New South Wales, Australia (Driscoll 1987). As hourly temperature and relative humidity data are not available for Uttaradit, hourly data from Don Muang (Bangkok) for 1970 were used, as these most closely approximated the average data for Uttaradit. Based on these, a management manual was produced using a time clock basis of fan operation.

A record system was established to record market inflows and outflows of paddy for the whole of the wet season.

Results and Discussion

1994

While the testing of aeration drying did not commence until very late in the wet season harvest (16 August), it did provide the opportunity to test the approach at the most difficult time of the year. Because of the commercial nature of the market centre, strictly controlled conditions could not be enforced. Delays were experienced in starting because of the difficulty of concrete pad drying of paddy to the intended initial moisture content of 18–19%. Actual initial moisture content was 19.8% for the first 28 t loaded, and 21.9% for the remaining 26 t. Conditions were exacerbated by a motor failure after 2 weeks, resulting in a halt in aeration for 8 days. The temperature of the grain was approximately 50°C at commencement, and while aeration then maintained the stack at 28–31°C, during the period of motor failure, temperatures reached almost 64°C above the drying front.

The fan was run continuously for the first 2 weeks but after the motor failure the intention was daylight use only. For a variety of reasons, this was not adhered to. Over the period of the test (37 days) the fan operated for 490 hours. During that time, the estimated total time that relative humidity was below 80% was 172 hours so the fan was operated often to no effect. The fan size was larger than required (to allow for future extension of aeration) and the stack was over-dried (aeration continued until the top of the

stack reached 14.5% moisture). As a consequence the cost of drying of approximately 100 Baht/t (about US\$4/t) was unacceptably high.

Despite the problems there was no difference in grain yellowing between this grain and the paddy that had been concrete pad dried and stored without aeration. These and other details are shown below in Table 1. The large difference in percentage head rice yield shown in the Table can be largely but not entirely explained in that, due to error, the last 26 t of the aerated stack (48%) was Chainat variety, whereas all other grain used was Suphanburi 60 which has a lower average head yield. Irrespective of any differences, the trader purchasing the rice did not differentiate between the two stacks and paid the same price/t for each.

Table 1. Details of aeration and grain characteristics for paddy drying demonstration 1994.

| Paddy characteristic | Aerated | | Unaerated | |
|------------------------------|---------|-------|-----------|-------|
| | Initial | Final | Initial | Final |
| Grain moisture (% wet basis) | 20.9 | 13.0 | 14.7 | 12.1 |
| Head rice (%) | top | 53.1 | 58.3 | 39.8 |
| | middle | – | 55.9 | – |
| | bottom | – | 60.5 | – |
| Grain yellowing (%) | top | 0.29 | 1.36 | 0.25 |
| | middle | – | 1.41 | – |
| | bottom | – | 0.19 | – |
| Storage period (days) | 72 | | 62 | |

1995

Despite a much longer lead time in 1995, a series of mishaps delayed commissioning of the new store and aeration system until the end of July (the end of donor assistance). At the time of this conference, preliminary information obtained from Tron Central Grain Market was that 3 weeks of deliveries occurred after commissioning, yielding a total of less than 500 t of paddy. None was totally dried by aeration but approximately half was stored and aerated for 3–5 days and then sold. Thus, the system has yet to be evaluated for wet season drying.

The simulation runs carried out indicate that, over the period of wet season deliveries, some 800–1000 t of wet paddy could be aeration dried in the new store, at an estimated cost of 34 Baht/t. However, even given full use, this only represents 10–12% of the 1995 wet season deliveries (see Table 2). Furthermore, full and efficient use of ambient temperature aeration drying can occur only in conjunction with a hot air dryer used for first stage drying. Of the 95 days of wet season deliveries, only 47 were suitable for any degree of concrete pad drying.

Table 2. Pattern of paddy deliveries, Tron Central Market 1995 wet season.

| Time period | Quantity received (t) | Quantity disposed (t) | |
|-------------|-----------------------|-----------------------|--------|
| | | Wet | Dried |
| 27-31/5 | 313.6 | n.r. | n.r. |
| 01-05/6 | 615.7 | 272.3 | 166.9 |
| 06-10/6 | 509.8 | 198.3 | 178.1 |
| 11-15/6 | 627.1 | 181.5 | 513.2 |
| 16-20/6 | 711.7 | 286.5 | 372.6 |
| 21-25/6 | 800.2 | 275.0 | 430.0 |
| 26-30/6 | 632.8 | 481.0 | 291.6 |
| 01-05/7 | 226.3 | 126.3 | 134.7 |
| 06-10/7 | 766.0 | 539.5 | 117.4 |
| 11-15/7 | 707.3 | 551.2 | 160.1 |
| 16-20/7 | 594.8 | 413.5 | 151.6 |
| 21-25/7 | 714.1 | 464.3 | 269.4 |
| 26-30/7 | 298.3 | 384.0 | - |
| 31/7-04/8 | 377.3 | 218.1 | 57.9 |
| 05-09/8 | 118.9 | 117.5 | - |
| 10-14/8 | 132.5 | 131.8 | - |
| 15-19/8 | 118.0 | 37.9 | 36.3 |
| 20-24/8 | 75.4 | 51.7 | 40.5 |
| 25-29/8 | 2.4 | - | 42.6 |
| Total | 8342.2 | 4750.4 | 2964.9 |

Conclusions

Ambient temperature aeration drying of paddy during the wet season can be successfully carried out in the northern region of Thailand, but heat-assisted aeration and 'dryeration' will be more practical than aeration drying alone. Despite training, farmer cooperatives have yet to determine how to best operate aeration systems.

Acknowledgments

Dr Somchart Soponronnarit of King Mongkut's Institute of Technology Thonburi, Thailand provided valuable technical advice. Dr Robert Driscoll and Dr George Szrednicki of the University of New South Wales, Australia provided a copy of the simulation program DRY and advice. Dr Maitree Naewbanij and staff of the Department of Agriculture, Thailand provided valuable assistance with temperature and relative humidity logging, and laboratory analyses.

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Use of Existing Pig Pens as Drying Bins for Wet Season Paddy Harvest

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THREE major constraints to farmer adoption of mechanical dryers are their high initial investment, high drying costs, and low utilisation rate. In the Philippines, farmers have to invest about PHP34 000 (during October 1995 ca 26 Philippine pesos (PHP) = US\$1) for the lowest cost mechanical dryer—a flat-bed dryer with a kerosene burner—which will only be used for about a month per year. Generally, farmers think they need mechanical dryers only during the wet-season paddy harvest, when the least cost dryer—sunshine—is not available or is unpredictable. During the dry season and in the absence of incentives to deliver higher quality grain, mechanical dryers are no match for sun drying.

Farmers usually tend at least one pig for cash purposes and pig pens are thus common structures in farms. Farmers with more than one hectare landholding usually own a power tiller, or have means to rent one for their needs. A pig pen and an engine provide a means for facilitating farmer adoption of mechanical drying.

A scheme to reduce initial investment and drying costs, and offset low utilisation rate by utilising existing pig pens as flat-bed, batch type drying bins, existing power tiller engines as prime movers, acquiring dryer components by modules, and using rice hulls for drying fuel, has been tested in Tarlac, Philippines.

Materials and Methods

The dual-use drying bin

A farmer in Tarlac, Philippines, who owns a tiller powered by a 5 h.p. diesel engine was selected as cooperator. Beside his house was a 2.6 × 3.5 m pig pen. The concrete wall and flooring were utilised as a drying bin. A 50 × 150 mm wooden beam was placed transverse to its length to support six detachable 1.8 ×

0.8 m wooden-framed BI sheet with 2 mm perforations. Concrete was poured on top of the existing pen wall to make an additional 0.36 m high enclosure. A 42 cm diameter blower housing was fitted permanently to the middle of the narrow side of the pig pen. Adjacent to this, a concrete base for the engine and straightener-vane blower system was installed. An IRRI-designed portable step-grate rice-hull furnace completed the system (Fig. 1).

The scheme involved raising pigs in the pen from November to July, then using it as a drying bin for the wet-season harvest months. The farmer either dries his own harvest and stores it for a better price, or provides paid drying services to his neighbours.

Performance tests

The pig pen drying bin–rice hull furnace (PDB–RHF) batch dryer system was tested using the RNAM test code for batch dryers and IRRI batch dryer test procedures, with slight modifications to suit available instruments. The furnace temperature, drying and ambient air temperature, ambient and exhaust relative humidity, grain moisture changes, and rice hull and diesel fuel consumption were monitored as drying proceeded. Batches of grain were dried under day- and night-time conditions.

Economic analysis

The profitability of the dryer was analysed, in comparison with that of a typical flat-bed dryer (FBD) and using utilisation rates of 30, 40, 50, and 60 t/year (15–30 days per year, 2 batches per day), and price differences of PHP1 to PHP6 (based on present prices). For other assumptions see Table 1.

Results and Discussion

Dryer performance

Under daytime ambient conditions ($T = 34.6^{\circ}\text{C}$, r.h. = 56.6%) and a drying air temperature of 44°C , paddy of 21% moisture content was dried to 14% in 5.7 hours

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or 1.18%/per hour moisture removal (or 14.8 kg H₂O/hour). It was difficult to sustain the combustion of rice hulls, hence the variation in drying air temperature. This also caused losses in drying time. There was, at most, a 3°C drying air temperature variation within the plenum, which is typical of flat-bed dryers. The grain depth of a batch of 1 t was 16.5 cm, and for 2 t was 30.5 cm.

Under night-time ambient conditions ($T = 26.6^{\circ}\text{C}$, r.h. = 76.5%) and a drying air temperature of 37.4°C, paddy of 21% moisture content was dried to 16% in 7.4 hours or 0.77%/per hour moisture removal rate. The drying air temperature could not be increased to 43°C because of low ambient air temperature and ambient relative humidity, characteristic of evening conditions.

It took 0.7–1.3 person-hours to load the wet grain and 1.5–2 person-hours to unload the dry grain. Rice hull consumption was 7.0–9.6 kg/hour and diesel fuel consumption 0.44–0.52 L/hour.

Economics of the PDB–RHF dryer

Like any mechanical dryer, the economics of PDB–RHF is sensitive primarily to the price difference between wet and dry paddy, and secondly to annual utilisation rate. However, because of lower initial investment and drying cost than the FBD, it is less sensitive to these two factors.

At a price difference of PHP1, investing in a 1 t dryer is not economical, even at an ideal utilisation rate of 60 t/year. At a price difference of PHP2/kg, the PDB–RHF dryer becomes profitable, while the FBD is still not so. At a price difference of PHP3/kg, the economics improved for both types of dryers, even for 30 t/year utilisation rate (Fig. 2), for which the annual net benefits for FBD and PDB–RHF were PHP27047 and PHP39197, respectively. This corresponds to payback periods (PBP) of 2.4 and 0.9 years, respectively.

The price difference for 1995 wet-season paddy was PHP6–7/kg, and for 1994 dry season paddy PHP3–P3.5, indicating that there are good prospects for increased adoption of mechanical dryers.

The drying cost as per cent of wet paddy was lower for the PDB–RHF system, ranging from 7.5–11.5% compared with the 12.7–19.6% of the FBD.

The lower investment and drying costs resulting from dual use of the drying bin, multiple use of the engine, and use of rice hulls for drying fuel mean that the owners of PDB–RHF systems would recover their investment more rapidly. In future applications, to further lower the drying cost, the dimensions of the pig pen-drying bin may be increased to bring its drying capacity per batch to 2 t or more.

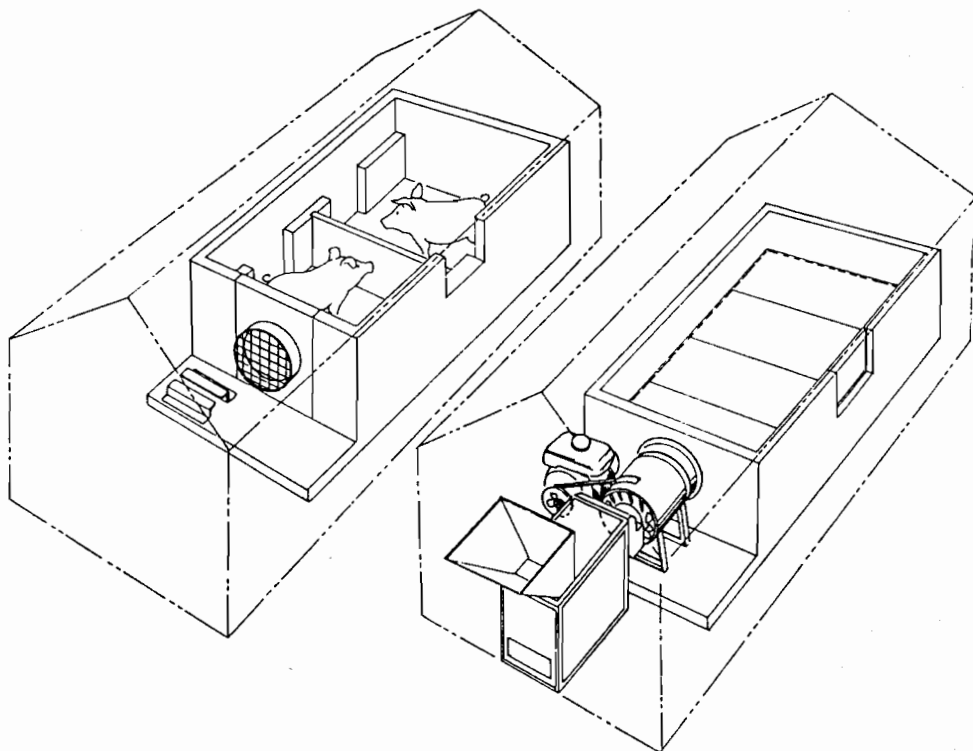


Figure 1. The pig pen drying bin-rice hull furnace (PDB-RHF) concept.

Table 1. Basic data used in economic analysis.

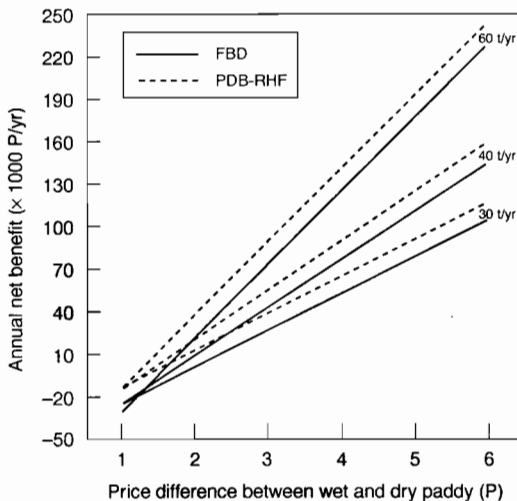
| | FBD ^a | PDB-RHF ^b |
|-------------------------------------|-------------------|----------------------|
| Investment cost (PHP ^c) | 64,000 | 34,000 |
| drying bin | 34,000 | 22,000 |
| diesel engine | 20,000 | n.a. ^d |
| rice-hull furnace | n.a. | 12,000 |
| shed | 10,000 | n.a. |
| Drying capacity | 1 t in 8–10 hours | 1 t in 8–10 hours |
| Utilisation rate (days/year) | 15, 20, 30 | 15, 20, 30 |
| No. of batches/day | 2 | 2 |
| Labour requirement | | |
| operation | 1/batch | 1/batch |
| loading/unloading | 1 person-hour/t | 1 person-hour/t |
| Fuel requirement | | |
| diesel | 0.5 L/hour | 0.5 L/hour |
| rice hull | n.a. | 10 kg/hour |
| kerosene | 2 L/hour | n.a. |
| Repair and maintenance cost | 10% 1C | 10% 1C |
| Labour cost | PHP100/person-day | PHP100/person-day |
| Price of wet paddy (26% m.c.) | PHP5/kg | PHP5/kg |
| Price of dry paddy (14% m.c.) | PHP6–12/kg | PHP6–12/kg |
| Interest rate | 24% | 24% |

^a FBD = flat bed dryer system (kerosene burner).

^b PDB-RHF = pig pen drying bin-rice hull furnace system; assumes farmer already owns a diesel engine or can rent one at PHP100/hour.

^c During October 1995, ca 26 Philippine pesos (PHP) = US\$1.

d.n.a. = not applicable.



It was observed that the farmer's wife used the heated top surface of the furnace to roast *tupig* (a native sweet delicacy). This suggested the concept of a rice hull furnace-cum-stove to further increase the utility of the furnace.

Conclusions and Recommendations

The tests indicated typical flat-bed batch dryer performance in terms of factors such as drying air temperature variations within the plenum and grain moisture variations. With skilful tending of the fur-

Figure 2. Annual net benefit of a flat-bed dryer and the pig pen drying bin-rice hull furnace (PDB-RHF) dryer system at varying price differences between wet and dry paddy, and various utilisation rates.

nace to maintain a plenum temperature of 40–50°C, a drying time of 5–6 hours is possible for a 1 t batch of wet paddy for typical daytime conditions, or 8–10 hours for a 1 t batch of wet paddy for typical nighttime conditions.

The average rice hull consumption during the tests was 8.32 kg/hour, while an average of 0.5 L/hour of diesel fuel was used. The rice-hull feeding and ash removal system for the furnace need to be improved for a more uniform and sustained furnace temperature.

Based on shorter drying time and lower moisture variation, the recommended depth of grain on the bin is from 16.5–25.4 cm (this corresponds to 1–1.5 t of wet paddy per batch).

Raising of pigs must be timed such that the pig pen has been vacated before the wet-season paddy harvest.

The PDB–RHF was economically attractive because of its low investment and drying costs. It becomes profitable at a price difference between wet and dry paddy of PHP2 if its utilisation rate is at least 30 t/year. To make the PDB–RHF system more economical and thus more acceptable, the capacity per batch may be increased, and a rice-hull furnace-cum-stove may be designed for all-year round cooking, and as furnace during wet-season paddy drying.

Case Studies on Moisture Problems in Guyana Brown Rice

D. Permaul*

In 1991, the Guyana Government began to deregulate the rice industry. This started a steady increase in rice production culminating in the largest ever exports of rice from Guyana, some 183 000 t in 1994. Much of the rice exports are semi-processed. An analysis of rice export figures for the past 5 years from Guyana shows that increasing amounts of brown rice (known as 'cargo rice' in Guyana) are being exported (Table 1). Millers and warehouse managers thus have to manage increasing amounts of brown rice over several months, an aspect of the business which is largely unfamiliar to them since in the past they have handled mostly paddy and milled rice.

Table 1. Guyana brown (cargo) rice exports as a percentage of total rice exports.

| Year | Total rice exports (t) | % Cargo rice(t) |
|------|------------------------|-----------------|
| 1990 | 61 000 | 49.4 |
| 1991 | 41 000 | 74.1 |
| 1992 | 115 000 | 46.3 |
| 1993 | 124 000 | 61.7 |
| 1994 | 183 000 | 84.2 |

Source: Guyana Rice Export Board, unpublished data.

Within the past two years there have been cases in which Guyana brown rice began to deteriorate in storage. This study examines three of these cases and tries to determine what went wrong to cause the spoilage both from a scientific and managerial perspective. Specific recommendations designed to minimise such losses are discussed.

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Case 1

Facts

Rice storage and processing facility A produces about 20 000 t of rice annually. Paddy at high moisture is processed into brown rice for export. Rice is stored in 400 t steel silos until ships arrive. Recently, rice in 4 silos (1600 t) heated up, and eventually developed a strong musty odour. Samples collected from various depths in the grain bulk were examined by the Government Analyst Department and found to contain fungi, mainly the genera *Aspergillus* and *Penicillium*. Moisture content of the samples was determined using a calibrated Motomco Model 919 meter. The moisture content of all samples was between 15 and 16%. The entire consignment of 1600 t was declared unfit for human food and had to be sold as animal feed at about 20% of its unspoiled value.

Findings

The main findings of discussions with company personnel were as follows:

- Management experimented with varying paddy moisture content so as to obtain optimum head rice recoveries. It was determined that using variety Rustic at 14% moisture content, the best head rice yields were obtained.
- After each pass through the artificial dryer, paddy was immediately returned to the dryer without being allowed time to equilibrate. Upon achieving 14% moisture content the grain was immediately dehulled for storage prior to shipping.
- Moisture content of rice was not determined after processing or during storage in silos.
- Silos were not equipped with temperature sensors to detect changes in the grain bulk.

Solution

It seems that in this case the grain, after passing through the dehulling process, might have been at a moisture content which was unsafe for storage or was still equilibrating, resulting in a higher storage mois-

ture content. In either case, this high moisture could have resulted in fungal proliferation.

Secondly, the quantities with which the moisture content/head yield experiment was carried out were far too large and hence became costly in the event of failure.

Monitoring moisture and temperature is an integral part in loss prevention in stored grain. Moisture meters were available to the officials but were not used. The silos too need to have a reliable system of measuring temperature rises in a bin. Additionally, the experimental methodology adopted must be more rigorous so that scientific conclusions can be gleaned.

Case 2

Facts

Rice storage and processing facility B produces about 15 000 t of rice per year. As in case A, paddy at high moisture is processed into brown rice for export. Rice is packaged in woven 50 kg polypropylene bags and stored in stacks of about 1000 t until shipped.

One of these stacks heated up and a mild odour was evident. Before it had been observed that the rice was beginning to deteriorate, 300 t were loaded onto a ship and eventually had to be removed manually. The entire consignment of 1000 t was redried and milling yield was reduced.

Findings

- The moisture content of paddy at milling was high as shown by records.
- There was a delay between the time the Quality Control Department indicated that the milling moisture was high and the time action was taken to arrest the problem.
- Weekly quality reports on cargo rice were not made.
- A cargo rice moisture chart was only recently produced.
- Silo drying staff lapsed in the amount of moisture removed from a given consignment of paddy at a specific moisture content.
- Paddy of different moisture has been stored in the same bin.
- Staff involved in the processing and storage of rice were poorly supervised.
- The national regulatory body was tardy in determining the moisture content and temperature of the affected shipment.

Solutions

- Moisture content at the time of milling should not exceed 13%. This can be achieved by the following
 - appropriate solar or artificial drying;
 - moisture checks on incoming paddy, paddy leaving after each drying pass, paddy that has been

tempered for a minimum of 8 hours, paddy that is stored in bins and bags and, on a half-hourly basis, paddy that is going to the mill. Results must be used to make timely decisions on drying, storage, and milling;

- twice daily physical examination of paddy storage bins for heating, condensation, and increase of moisture, and taking appropriate action such as drying and aeration.
- Quality control reports with the following information should be made on all cargo produced:
 - half-hourly moisture content of cargo rice produced. This should not exceed 13.8%. As soon as this happens, milling should be stopped and only paddy of suitable moisture milled. The rejected batch should be dried;
 - quantity of cargo in stacks;
 - factors such as discoloration, yellowing, insect infestation, moisture content, paddy, chalky, green, insect damaged, etc. This should be done weekly;
 - temperature of the stacks and bins. Bin temperature will need engineering work. Stack temperature can be measured with a grain thermometer.
- The Quality Control Department should be empowered to stop the mill if the moisture content is unacceptable.
- Management supervision must be improved to a level where timely decisions can be made, especially with reference to critical factors such as moisture content.

Case 3

Facts

Private entrepreneur C exports Guyana cargo rice in 20 t steel containers. These are fumigated, sealed, and stored in the open at wharves before export. One consignment of 20 containers stored for 4–5 weeks deteriorated. Several sections within the grain bulk of each container were caked, musty smelling, and were rejected for export. Much of this rice was sold at a very low price as animal feed.

Findings

- Moisture content was not measured before loading. Samples taken showed a moisture content of 15–16%.
- Monitoring of containers after fumigation was not carried out. Such monitoring was not easy as a result of wharf and customs regulations.

Solutions

The grain in this case might have been at a safe or unsafe storage moisture. Even if it had been safe initially, moisture condensation caused by differential

heating during the day might have created conditions for spoilage.

- Moisture content of potential export rice must be measured with an accurately calibrated meter and should not exceed 14%. Ideally, moisture content should be about 13.5% for cargo rice.
- There should be timely shipping of containers. When not possible, containers should be kept under cover.

Discussion

Spoilage organisms

In each of the three cases described, high moisture seems to have contributed to the deterioration. The fungi most consistently associated with incipient grain deterioration are members of the genera *Aspergillus* and *Penicillium* (Lin 1986). Apart from the requirements of a suitable substrate and atmospheric conditions, the most critical conditions for the growth of fungi are summarised in Table 2. Clearly, once rice is stored at an equilibrium moisture content which is equivalent to slightly less than 70% relative humidity, fungal deterioration can be avoided.

Once rice is moist enough for fungi to grow there is rapid proliferation which may be associated with discoloration (Phillips et al. 1989), increase in chalky grains (Quitco and Ilag 1982), mycotoxin contamination (Pitt 1991) and, finally, a caked, musty, rotting mass (Christiansen and Sauer 1982), if conditions remain favourable.

Integrated strategies

Spoilage can be reduced if integrated strategies are applied along the whole postharvest chain in Guyana.

Maintenance of machines and equipment

Faulty or inefficient machinery takes longer to process rice and increases the risk of fungal attack. Critical pieces of equipment such as elevators, conveyers, dryers, and cleaners deserve much more care and maintenance than others. Maintenance and calibration of moisture meters must also form part of this program.

Sanitation and hygiene

Good sanitation eliminates conditions which favour storage pests and minimises infestation arising from such reservoirs. Insect infestation is known to initiate heating in grains (Howe 1962).

Harvesting

Before harvesting, the combine should be cleared of previous grain debris or treated with an insecticidal fog to eliminate residual infestation. Combine setting and speed must be adjusted and fine-tuned to derive maximum yield, minimum damage to the grain, and low dockage. Dockage may contribute to 'hot spot' formation in grain (Hall 1963).

Drying

Proper paddy drying is probably the single most important act to reduce fungal spoilage in cargo rice. Where artificial dryers are used, the manufacturer's recommendations should be followed.

Storage

Having dried the incoming paddy to 12–13% moisture content it may then be stored in clean bags, silos, or flat-bulk stores. Stocks should be built on dunnage to minimise 'wetting' of bottom bags. Adequate space must be left around stocks to facilitate inspection, sampling, pesticide application, and grain removal.

Inspection and sampling

Once paddy is stored, the need for inspection and sampling, followed by accurate measurements, becomes critical. These activities are to:

- locate unsanitary conditions conducive to pest multiplication;
- find infestation that already exists; and
- determine what, if any, control measures are needed.

During this procedure, moisture content of stored paddy and temperature of stacks and bins should be closely monitored so as to provide timely information on incipient deterioration.

Table 2. Approximate conditions of relative humidity and temperature for the growth of common storage fungi.

| Fungus | Minimum relative humidity (%) | Minimum temp. | Optimum temp. (°C) | Maximum temp. (°C) |
|-------------------------------|-------------------------------|---------------|--------------------|--------------------|
| <i>Aspergillus restrictus</i> | 70 | 5–10 | 30–35 | 40–45 |
| <i>Aspergillus glaucus</i> | 73 | 0–5 | 30–35 | 40–45 |
| <i>Aspergillus candidus</i> | 80 | 10–16 | 45–50 | 60–65 |
| <i>Aspergillus flavus</i> | 85 | 10–15 | 40–45 | 45–50 |
| <i>Penicillium</i> spp. | 80–90 | 5–10 | 20–25 | 35–40 |

Source: Lin 1986.

Processing of paddy

The moisture content of paddy entering the mill must be rigidly controlled so as to produce cargo rice not exceeding safe storage moisture levels.

Cargo rice stacks produced must also be monitored during storage. This kind of monitoring is the responsibility of quality control personnel and a practical regime must be worked out. The regulatory body can also be asked to monitor moisture content of cargo rice entering trade.

Stock management

Whenever it is compatible with the objectives of management, rice brought into storage should be the first to leave, whether it is being sold or scheduled for milling. This lowers time spent in storage and minimises the risk of spoilage.

Record keeping

Properly kept records are especially helpful in making decisions which may affect grain moisture levels, and over a period of time provide a source from which in-depth analyses can be carried out pertaining to drying.

Conclusions

High moisture brown (cargo) rice can deteriorate rapidly under Guyanan conditions, leading to severe economic losses. In all three cases examined, high moisture and subsequent fungal proliferation seem to have been responsible for the spoilage. If high moisture cargo rice is produced, then it means that moisture content in rough rice or paddy is not controlled adequately. None of the series of measures identified can individually ensure safe levels of moisture in cargo rice, but collectively can minimise the kind of damage detailed in the cases here. Many of these measures are interdependent. Failure to store dried paddy on pallets or dunnage, which helps to prevent moisture migration from the floor to the grain, serves

to illustrate this interdependence. As Guyana begins to deal more in brown rice, the need to apply the strategies outlined here will become more critical if spoilage is to be kept within manageable limits.

Acknowledgment

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Grain Drying in a Batch Fluidised-bed Dryer

Pham Cong Dung*

Abstract

Fluidisation has long been used for grain drying around the world. The principal advantages of this technology are: the heat and mass transfers between the airflow and grain are very great; the dryer is simple and small, so the initial investment is rather low; and the moisture content of the product is uniform. In Vietnam, fluidisation has not yet been used widely, so it is necessary to study the effect of factors such as air temperature and velocity on time of grain drying in order to optimise fluidised-bed drying. A series of laboratory-scale experiments was conducted on maize and paddy using a batch fluidised-bed dryer. The following conclusions were drawn.

- The air velocity has no significant effect on drying rate. After fluidisation, further increases in air velocity do not affect drying rate. It is thus necessary to determine a stable hydrodynamic regime for the fluidised bed.
- The drying air temperature has a significant effect on drying rate. The drying rate with air at 95°C is approximately twice as fast as with air at 15°C. An empirical formula which shows the relationship between drying time and the air temperature for some agricultural products was obtained by applying the least square method to the experimental results.

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Development of a Conduction-type Dryer for Paddy

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SUN DRYING is an inexpensive and convenient method of drying crops. In rice-farming areas, however, it is undependable when paddy is harvested in the wet season and, because of clouds and rain, drying is delayed. This problem has led to the development of a variety of low-capacity paddy dryers. None of the present designs has been widely accepted, generally because the cost is high for a device that is used only when sun drying is prevented by rain or overcast weather. With this in mind, a simple, low-cost 'heated floor dryer (HFD)' which complements sun drying and utilises rice straw as fuel has been designed and developed, and a pilot model tested.

The basic concept is that the HFD will be used only when sun drying is prevented by weather and it will serve to pre-dry paddy to a moisture content of about 18%, which is adequate for temporarily storing the grain until weather allows complete drying under the sun. This is an extension of the concept of conduction drying, in which a metal floor is heated by circulating hot water, and the paddy is dried on the hot floor in a way similar to traditional drying on a hard floor under the sunlight. The principal attribute is that it is a simple technology that, during cloudy or rainy periods, complements sun drying. Moreover, the same labour force used for sun drying is used for heated floor drying at the time when workers would otherwise be idle due to cloudy or rainy weather.

As shown in Figure 1, the main components of the HFD are:

- a furnace in which rice straw is burned to heat water to the desired temperature (e.g. 90°C);
- a pump for circulating the water from the furnace water jacket to the drying floor;

- a metal drying floor, heated internally by circulating water; and
- a roof to protect the floor from rain.

By locating the HFD next to the conventional sun-drying floor, it is easy to push the paddy from sun dryer to HFD when clouds appear. The capacity of the dryer is 1 t/day, which meets the needs of small groups of farmers such as milling and marketing cooperatives in areas where labour-intensive drying is more appropriate than mechanised drying.

The drying rate is controlled by the vaporisation process rather than by heat or mass transfer processes in such types of drying systems, and the following equation represents the true picture:

$$\text{drying rate} = K_1/\theta = K_2 \exp(-h_{fg}/RT)$$

where, K_1 and K_2 are constants, θ is drying time, h_{fg} is latent heat of vaporisation of water, R is the universal gas constant, and T is absolute temperature in kelvins (K). On solving the above equation and substituting the value of $h_{fg} = 9714$ cal/mole for water and $R = 1.987$ cal/mol K, we get:

$$\delta/\delta (1/T) [\log \theta] = 1803.97 \text{ K}$$

Therefore, as shown in Figure 2, the solid line drawn through the data has slope of the curve equivalent to 1803.97 K, which confirms the hypothesis that the rate-controlling step of HFD is vaporisation of water rather than heat and mass transfer.

The quality parameters of milled rice dried with HFD were also analysed. As shown in Figure 3, the grain breakage (per cent broken grains) is lower for HFD than conventional sun drying, even at a temperature of 90°C. The drying process appears to be satisfactory under conditions of high atmospheric humidity (80–90%), as occur during rainy periods. The grain breakage is substantially lower for HFD than traditional sun drying (e.g. 7–25% versus 30–66%). No parboiling effect was observed after drying the paddy with HFD.

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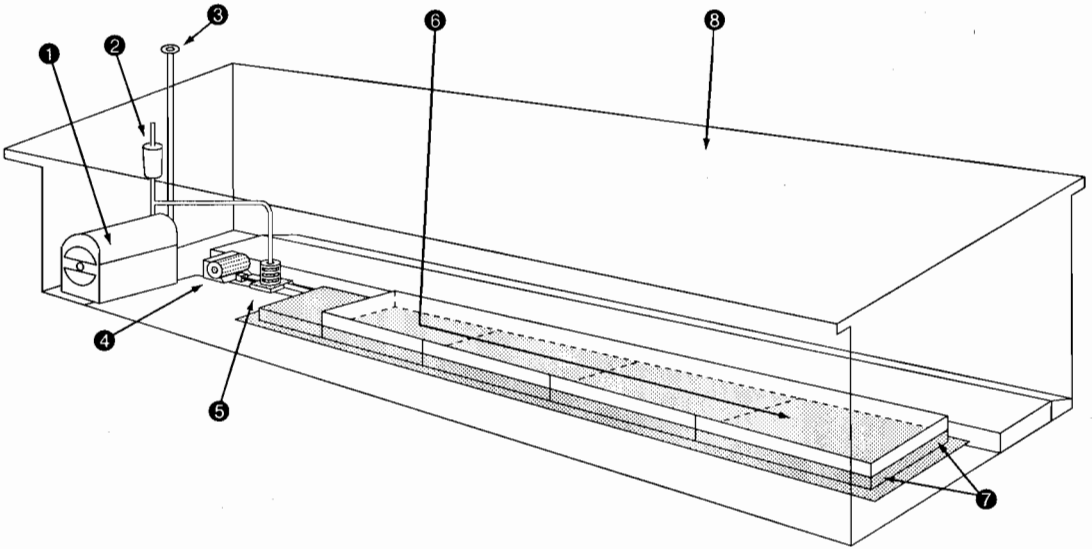


Figure 1. Schematic diagram of heated floor dryer showing different components: 1, boiler; 2, expansion tank; 3, chimney; 4, electric motor; 5, water pump; 6, drying plates; 7, wood support; 8, dryer shed.

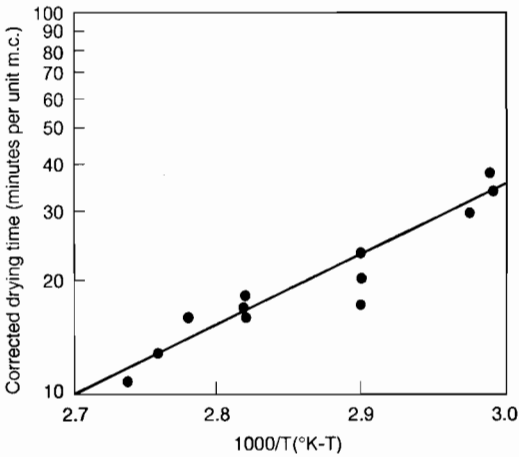


Figure 2. Logarithmic plot of corrected time versus the reciprocal of the floor temperature. The corrected drying time is the total drying time divided by the difference of initial and final moisture content of the paddy, i.e., in minute per unit moisture content change.

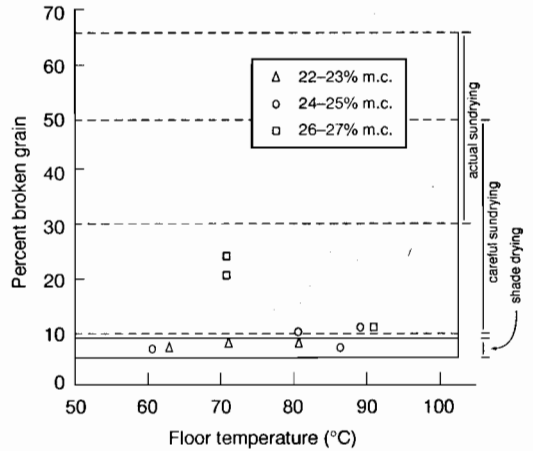


Figure 3. Comparison of grain breakage by heated floor dryer with sun and shade drying at different initial moisture content of paddy.

Rice Husk Furnace and Reversible Airflow Grain Dryer

P. Kuizon*

RICELANDS in the Philippines are mostly in small lots, less than 10 ha, having been inherited from generation to generation by an increasing number of heirs.

Land reform subdivided further the lots for tenant-farmer beneficiaries, most of whom have organised into cooperatives. Cooperatives need dryer capacities from 5 to 10 tons daily or several units of such capacity because rice is planted in at least 5 varieties.

If a single large dryer is used, the different varieties have to be mixed for drying. Mixing varieties of different kernel sizes does not promote efficient milling. For efficient milling, the different varieties must be dried and milled separately.

Furthermore, because paddy comes from many sources (members of the cooperative), it arrives at the dryer site in different moisture contents providing another reason for separate drying.

Use of Rice Husk in Grain Drying by Direct Heating

How the rice husk furnace came to be developed

When my wife and I put up a rice mill in 1970, we could mill only during sunny days as paddy was sun dried. Unfortunately, in the Philippines, the harvest season coincides with the rainy season.

We experimented with a kerosene-heated flat-bed dryer. After developing the dryer in about one year, farmers and millers brought their paddy to us for drying. They subsequently asked us to build dryers for them, and thus began our commercial production of dryers. Kerosene then was very cheap, P 0.20/L. Later, when an energy crisis hit the country, kerosene became too costly as a drying fuel: its cost went up more than 30 times.

Meanwhile, abundant unwanted rice husk was available in our rice mill. It had low moisture content and was probably the driest among the agri-wastes. This made it a good heating fuel if properly burned.

We experimented with three furnace designs that should produce not only smokeless combustion but also zero or negligible fly ash. Heating was direct for high thermal efficiency and lower production cost. It took almost two years to come up with a model of acceptable performance. It had stepped-grate, updraught flow of flue gas through the expanding volume of the combustion chamber, and was equipped with an ash settling chamber. Induced draft from a drying fan provided combustion air.

The two-face furnace

As demand for drying capacities grew, larger heat generating capacities of furnaces became necessary. The first model was good only up to 3 t paddy capacity. For larger heat generating capacity, we came up with a design of 'two-face' stepped-grate furnace which had two furnaces installed facing each other (Fig. 1). The advantage in this design is that the two furnaces facing each other without any wall between them, *burned each other* by their radiant heat, resulting in a more complete combustion. Each furnace face had an inclined feed hopper. A vibrating ash grate unloaded ash.

Fuel consumption

As tested by the National Postharvest Institute for Research and Extension (NAPHIRE) in 1982, fuel consumption was 4.26 kg/hr rice husk per t of paddy loaded into the dryer. The same test also showed our dryer had the highest drying system efficiency among the six Philippine-made dryers tested and evaluated that year.

Improvements on furnace

1. Fuel hopper is equipped with a rotary-vane feeder
2. Scraper-type ash grate for uniform unloading of ash
3. Positive temperature-control damper at furnace outlet for quick temperature regulation
4. Semi-circular refractory top cover for durability.

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At present, commercial furnace models are:

1. One-face furnace type for dryer capacities of 3 t and below
2. Two-face model for capacities larger than 3 t (at present, the most saleable dryer size has 10 t paddy capacity)
3. Multi-fuel model to burn not only rice husks but also peanut hulls for peanut drying and maize cobs for maize drying. However, dry maize cobs are not readily available during the wet season when their moisture content is as high as 50% (the required moisture content for smokeless combustion is 12%). Such dryers should have a backup kerosene or diesel burner for full dryer usage.

The Ricehull-fired Reversible Airflow (RFRA) Grain Dryer

In a flat-bed dryer, the tendency is for the bottom layer of the grain to overdry, while the top layer remains wet, if the drying airflow is upward only. To remedy the excessive moisture gradient it is necessary to stop dryer operation at about half the expected drying time to mix the grain. This is a very laborious, dusty and itchy job, and time is lost. The purpose of mixing is actually to exchange the top and bottom layers of grain. It is much simpler to reverse the airflow rather than to turn over the grain batch.

We experimented with a drying bin so that drying airflow could be reversed alternately, upward and downward (Figs 3 and 4). An air reversing valve ARV was installed between drying bin DB and drying fan DF. Wide grain-loading doors GLD and vent doors VD at lower plenum chamber were provided. When airflow is upward, grain-loading doors are opened to allow used air to exhaust, vent doors are closed; when airflow is downward, grain-loading doors are closed and vent doors are opened. For rain-wet or dripping-wet paddy initial downward airflow enables gravity to aid in the removal of excess moisture. Air reversal is usually done only once. However, for dripping wet paddy, two air reversals are necessary

In manual mixing of paddy, it took approximately 2 hours by four men per ton. To reverse airflow with the air reversing valve, it takes less than 5 minutes. With reversible airflow feature, moisture content differences at top, bottom and middle layers are within 1%.

Multicrop capability

The RFRA dryer has multicrop capability, being able to dry copra, peanut, maize, etc.

Environmentally friendly dryer

The RFRA is environmentally friendly: i.e. noiseless (does not disturb neighbours during night-time operation), smokeless and dustless in operation. It is dustless because exhaust air with high relative humidity exits at a velocity below that which supports dust in air.

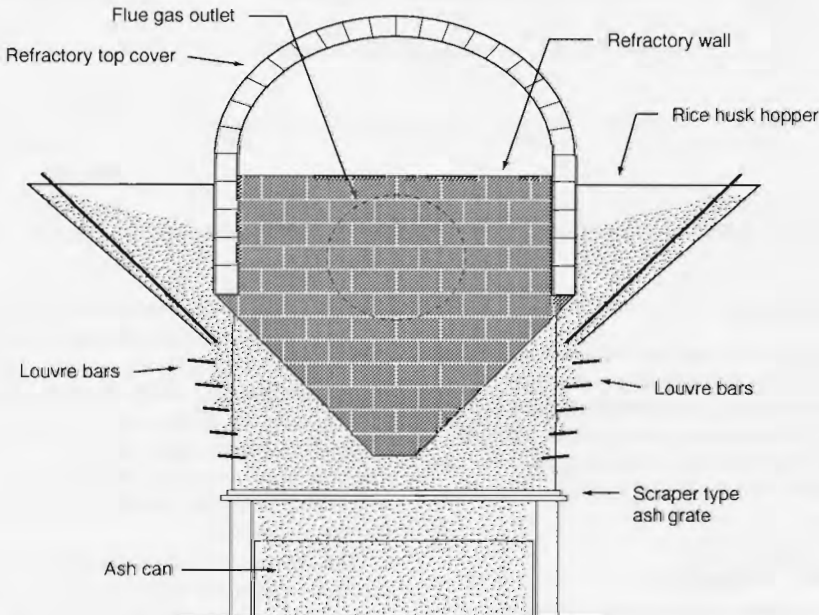


Figure 1. Double-sided rice-husk furnace.

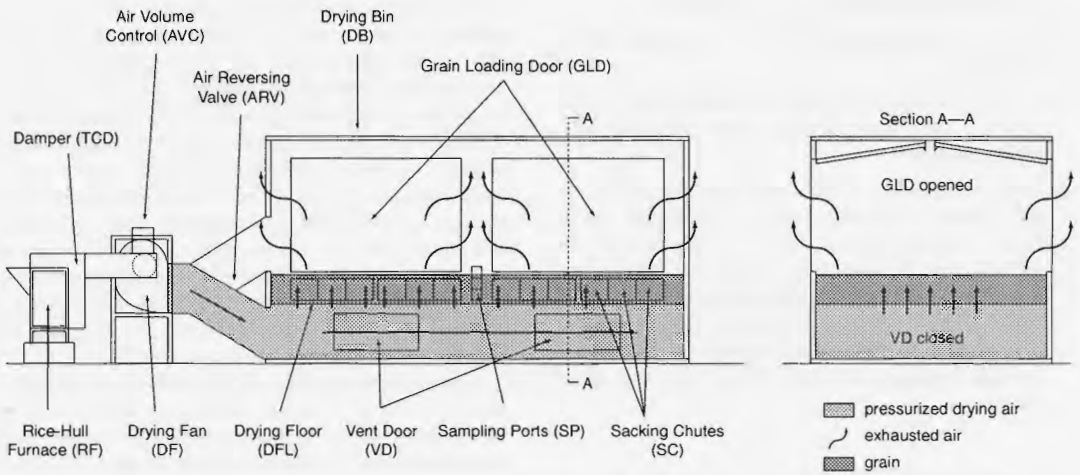


Figure 2. Rice-hull-fired reversible airflow grain dryer showing airflow in upward airflow mode.

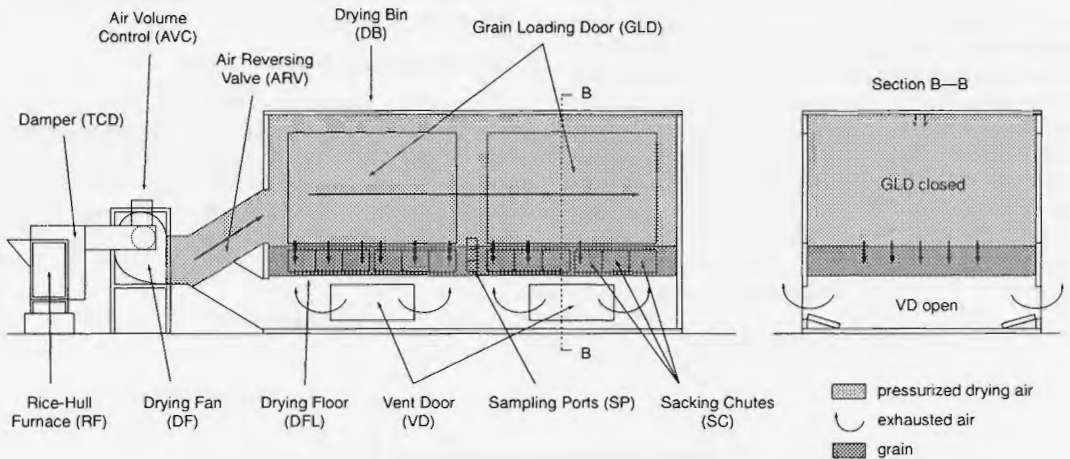


Figure 3. Rice-hull-fired reversible airflow grain dryer showing airflow in downward airflow mode.

Dryer standby power

Power interruption is not uncommon in the Philippines. Most of our installations have a standby diesel engine. Both the electric motor for the drying fan and the diesel engine are mounted on a special tilting base so that transferring the belt from one to the other can be done easily in one minute.

Marketing

The dryer was promoted by:

1. Sending brochures to prospective buyers
2. Visits by our sales representatives and dealers

3. In later years when the RFRA dryer gained acceptance, promotion was enhanced by favourable comments from our clients, especially those who made repeat orders for one or more dryer units.

At present, the RFRA dryer is probably the fastest-selling rice-husk-fired dryer in the Philippines because of its relatively low capital cost, low operating costs, negligible maintenance cost and being the easiest to operate.

The absence of sophisticated electric or electronic controls makes the dryer suitable for the Philippine countryside where skilled technicians are not available. The problem with the high-tech imported dryers

is that when controls fail, it means weeks or months of down time before costly repairs can be made by a competent technician.

Acknowledgments

P. Kuizon Enterprises acknowledges with gratitude the following for their valuable contribution to our efforts to develop a grain dryer that is probably the most practical for the Philippine countryside today:

1. International Rice Research Institute (IRRI) in Los Baños, Laguna, Philippines, for drying data
2. National Postharvest Institute for Research and Extension (NAPHIRE) for their test and evaluation in 1982 from which we obtained complete technical (operating) data
3. National Cottage Industry Development Authority (NACIDA) for extending a loan which served as

the initial capital in the commercial production of the dryer

4. Kalayaan Engineering Co., Inc. in Makati, Metro Manila, Philippines for supplying us with the drying fan and kerosene burner during our initial research and development.

Further Reading

The RFA dryer was featured in the following publications:

- 'Catalogue of Commercially Available Agricultural Machines in the Philippines' by the University of the Philippines in Los Baños, 1986
- Asia Pacific Monitor, United Nations, 1988
- 100 Selected Technologies from Asia and the Pacific, 1989.

Some Socioeconomic Aspects of Plans for Increased Grain Production in Papua New Guinea

Levi B. ToViliran*

PAPUA New Guinea (PNG) lies between latitudes 1 and 12°S, and longitudes 141 and 160°E, north of Australia, its closest neighbour. The country has a population of about four million, which depends almost entirely on agriculture. Agriculture is the main source of livelihood for over 85% of the population, contributing over 27% of gross domestic product (GDP) and over 14%, by value, of exports. The agriculture sector involves more than 75% of the country's labour force.

Agriculture Background

Over 90% of agricultural exports by value are contributed by the three major tree crops: coffee, cocoa, and coconut. Cardamom, chillies, and pyrethrum are minor cash crops, contributing less than 1% of exports by value.

The largest contributor to exports, at 60% by value, is the mining industry (copper, gold, and oil). The mining sector's contribution to GDP—22%—is lower than that of agriculture, and its capital-intensive and enclave features mean that it has weak linkages to the rest of the economy.

Agriculture will continue to be the main source of employment and the sector will provide broadly based growth of the economy in the future. It has enormous potential for development if continuing attention and emphasis are given to the production and marketing of food commodities such as beef, pigs, poultry, fish, fruit and vegetables, and rice. Recent additions to this commodity list include sugar, sheep, and honey.

Grain and Cereal Production

PNG produces little grain and cereals, with the exception of small amounts of maize and sorghum

grown commercially and for subsistence. An estimated PGK200 million (during October 1995 ca 1.33 Papua New Guinea Kina (PGK) = US\$1) is spent on the importation of grain and cereal products, rice being most important, followed by wheat for livestock.

Rice

Rice has become an increasingly popular staple food. Currently, 130,000 t are imported annually, at a cost of over PGK100 million.

Rice can be grown in PNG but there is little scope for promoting rice production in the smallholder sector without substantial protection.

Exploratory development projects are already under way, and rainfed or irrigated rice is grown by smallholders in a range of locations including Bereina and Cape Rodney in Central Province, the lower Markham Valley and Finschhafen in Morobe, Bogia in Madang, Maprik in East Sepik, Warangoi in East New Britain, and Oro Province.

Maize

Most maize is grown in the Markham Valley by two large-scale operators who produce 3500 t annually for stockfeed. The domestic stockfeed market requires approximately 12,000 t of maize annually, but only one third of this is produced locally.

Public investment project funding is provided to smallholders for grain and credit. Also provided is part funding for variety and fertilizer trials, both on station and farmers' fields.

Peanuts

Peanuts are a subsistence crop and have also been grown commercially for some years. Current production of only 100 t is sold on the open market and as confectionery in the retail formal market. Smallholder commercial production was established in the Markham Valley, but due to the unavailability of a market, the peanut butter factory was closed.

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Sorghum

Though sorghum used to be grown in large quantities for the livestock feed industry, pest and disease incidences and poor drying facilities have caused a large decline in production.

Sunflower

A limited amount of sunflower is grown in PNG, but some preliminary work has been undertaken by the agricultural research department.

Pulses

Pulses being grown in PNG include peas and beans. They are the main source of vegetable protein supplements. Pulse production needs to be expanded through research and extension-supported varietal introduction and crop improvement. For the industry to develop, processing and marketing assistance is also required.

Constraints

The lack of developed infrastructure, insufficient technology, ineffective and inefficient policy and planning strategies, difficult physiographic features, and lack of developed markets pose threats to the development of grain production.

Social and cultural factors have implications for the transfer of modern technology. Climatic conditions with unexpected unfavourable weather are also constraints that need to be considered.

Conclusion

PNG has the potential for local grain production (rice, maize, peanuts, sorghum, sunflower, and pulses). Climatic and environmental conditions are provisions contributing to the ability and/or potential. If given the proper direction and support, PNG can produce a significant part of its needs for these products. Any expansion in grain production to cater for the existing markets appears feasible, if support is provided for machinery and equipment acquisition and technical assistance to farmers.

Recommendation

The intention of the PNG Government's proposal for the establishment of a Grain Development Industry Corporation (GIDC) would be to boost production of rice and other grains. The Government has recommended that the corporation play a major role in assisting semi-commercial farmers to produce rice and grain consistently. It should also seek to facilitate the efforts of non-government organisations, the private sector, and credit suppliers in their endeavours to develop a smallholder industry. This would support the Department of Agriculture and Livestock's objective of promoting production of a range of food crops, some of which are currently imported, through industry-orientated research, development, and extension.

Further Reading

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Development of a Fluidised-bed Dryer for Paddy in Vietnam

Truong Vinh, Phan Hieu Hien, Nguyen Van Xuan,
Nguyen Hung Tam, and Vuong Thanh Tien*

A two-stage drying technique has been tested and promoted at Song-Hau Farm in the Mekong delta of Vietnam (Phan and Hung 1995). The farm introduced a second-stage, 80 t in-store dryer in 1994, which could gently dry paddy at 18–20% moisture content (m.c.) wet basis (w.b.) to 14% in about 4 days. The need now is to find some compatible, first-stage dryer, wherein freshly harvested paddy at high moisture (25–32% m.c.) is quickly dried to 18–20%.

Current dryers, such as columnar continuous-flow devices, cannot handle the above range of high moisture; paddy that is too wet simply does not flow in the drying column or sticks to the conveyor. Fluidised-bed drying is a promising alternative (Sutherland and Ghaly 1992; Tumaming and Driscoll 1993). The advantages and disadvantages of fluidised-bed drying have been discussed by several authors (Porter et al. 1984; Reay 1986; Hovmand 1987; Bahu 1991; Brooker et al. 1992). Two main advantages are: homogeneous drying due to thorough mixing of air and grain; and short drying time due to high heat and mass transfer rates with high air velocity.

The most recent development has come from Thailand, where a 1 t continuous fluidised-bed dryer has been adopted on a commercial scale (Soponronnarit 1995). Two disadvantages of fluidised-bed drying, namely high heat energy requirement and dusty output, have been overcome by using air recirculation and a suitable cyclone.

This paper describes the development of a fluidised-bed dryer in Vietnam for first-stage drying of grain. It outlines the design and the results of tests of the dryer, and gives an estimate of the cost of fluidised-bed drying.

Materials and Methods

Design of equipment

A 1 t fluidised-bed dryer (Fig. 1) has been designed at the University of Agriculture and Forestry (UAF), Ho-Chi-Minh City. The design has drawn much relevant information from Thailand. Soponronnarit and Prachayawarakorn (1994) reported parameters for a batch-type fluidised-bed dryer as follows: superficial velocity $V_{af} = 4.4$ m/s; grain thickness $d = 0.095$ m; specific airflow $V_s = 0.1$ kg/s.kg dry matter; drying temperature $T_i = 115$ °C; recirculation of drying air = 80%. Another recent development is a 1 t/hour continuous fluidised-bed dryer which could dry paddy from 25% m.c. (w.b.) to 19% in 2–3 minutes (Soponronnarit et al. 1996). Parameters used in this dryer were: $V_{af} = 2.3$ m/s; $d = 0.100$ m; $T_i = 115$ °C; recirculation = 80%. The drying floor was 0.3×1.7 m. Paddy was pre-cleaned before entering the dryer. We also received drawings of the drying bin components from King Mongkut's Institute of Technology, Thonburi, Thailand (KMITT); and suggestions from the KMITT team led by Professor Somchart Soponronnarit.

Based on the ample supply of rice husks in the Mekong delta, and the requirement of reducing drying cost, we have designed an automatic rice-husk furnace, rather than using an oil burner as in the KMITT design. Due to the low cost of rice husks, the recirculation was reduced to 50% while maintaining a drying temperature of 115°C. Dimensions of the drying bin and cyclone were modified slightly, to fit the current practice in Vietnam of not precleaning paddy before it enters the dryer. Calculations based on the balance of heat and mass transfer resulted in the following: drying bin surface = 0.3×2.0 m; drying air velocity = 3.6 m/s; and drying time = 2 minutes. Also, the drying fan was redesigned based on the airflow requirement of 2.2 m³/s at 2600 Pa pressure.

* University of Agriculture and Forestry, Thu Duc, Ho Chi Minh City, Vietnam.



Figure 1. The 1 t/hour fluidised-bed dryer fabricated at the University of Agriculture and Forestry, Ho-Chi-Minh City.

Experimental procedures

The fluidised-bed dryer has been fabricated at the mechanical workshop of UAF and installed at the Song-Hau Farm, Can-Tho Province in the heart of the Mekong delta (Fig. 2).

Tests were conducted in September 1995. The fan performance was measured before the tests (Fig. 3). Drying temperature was measured using a type-K thermocouple; exit grain temperature was measured by digital thermistor. Static pressure at various points was monitored with U-tube manometers. Dryer capacity was calculated by weighing the paddy leaving the exit spout over a 1.5 minute interval. Also

measured were grain layer thickness, furnace temperature, and rice husk consumption.

Paddy used in the experiments was very wet (>30% m.c. (w.b.)), which is common during the summer-autumn harvest season. There was one exploratory experiment with maize.

Results and Discussion

First experiment (14 September 1995)

Test conditions

Paddy: Initial moisture content = 34.7% (w.b.),
 Variety = IR-1055
 Bulk density = 480 kg/m³

Ambient air: Temperature = 28.5°C
 Relative humidity = 82%

Grain layer thickness = 8 cm

Drying temperature = 115°C

Results

Final moisture content = 18% w.b.
 Drying capacity = 630 kg/hour
 Exit grain temperature = 71°C .
 Total quantity dried = 2 t

Discussion

This was the experiment with several initial dryer adjustments, leading to low capacity, long residence time, and too low a final moisture content.



Figure 2. Operation of the fluidised-bed dryer at Song-Hau Farm, September 1995 .



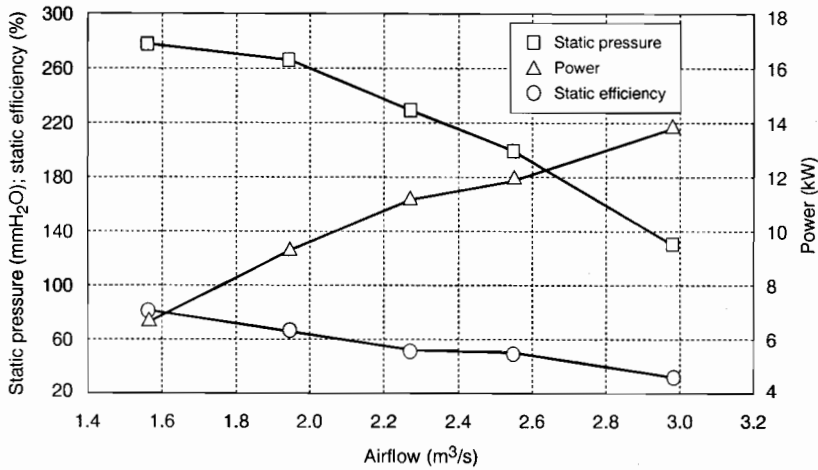


Figure 3. The fan performance curve of the fluidised bed dryer.

Second experiment (15 September 1995)

Test conditions

Paddy: Initial moisture content = 31.0% w.b.
 Variety = IR-1055
 Bulk density = 520 kg/m³
 Impurities: 2% by weight (7% by volume)

Ambient air: Temperature = 28°C
 Relative humidity = 89%

Results

Nine test runs were made. The results are given in Table 1.

Discussion

The tests had been planned as a factorial experiment. However, during the course of the experiments we found that the furnace thermostat could not maintain the drying temperature within the expected $\pm 1^\circ\text{C}$; the actual variation was $\pm 5^\circ\text{C}$. Thus, the results in Table 1 were pooled to obtain the average and standard deviation. Nevertheless, the data show the overall performance in the temperature range of 105–115°C. The dryer was operated with stable performance, with a capacity of over 1 t/hour. No blocking or jamming was observed during tests with a total quantity of 3 t of paddy. The distribution of the bubble layer was uniform. A 10% moisture reduction in wet paddy (from 31 to 20–22%) was confirmed.

Table 1. Results of paddy drying trials with a fluidised-bed dryer.

| Drying temperature (°C) | Grain thickness (cm) | Exit grain moisture (% w.b.) | Exit grain temperature (°C) | Capacity (kg/hour) | Head rice recovery ^a (%) |
|-------------------------|----------------------|------------------------------|-----------------------------|--------------------|-------------------------------------|
| 105 | 12 | 20.8 | 55 | 1032 | 48.7 |
| 110 | 10 | 22.8 | 66 | 1020 | 58.7 |
| 115 | 8 | 19.6 | 63 | 1260 | 52.5 |
| 115 | 12 | 22.0 | 59 | 996 | 53.4 |
| 110 | 10 | 22.7 | 65 | 1356 | 57.7 |
| 105 | 8 | 20.1 | 65 | 1500 | 56.7 |
| 110 | 10 | 22.0 | 59 | – | 56.2 |
| 110 | 10 | 21.4 | 60 | – | – |
| 110 | 10 | 21.4 | 60 | – | 51.5 |
| Average | | 21.4 | 61.3 | 1194 | 54.4 |
| S.D. | | 1.1 | 3.6 | 210 | 3.5 |

^a Fluidised-bed dried samples were further dried to 12% w.b. under the same conditions as shade dried samples, for which the head rice recovery was 52%.

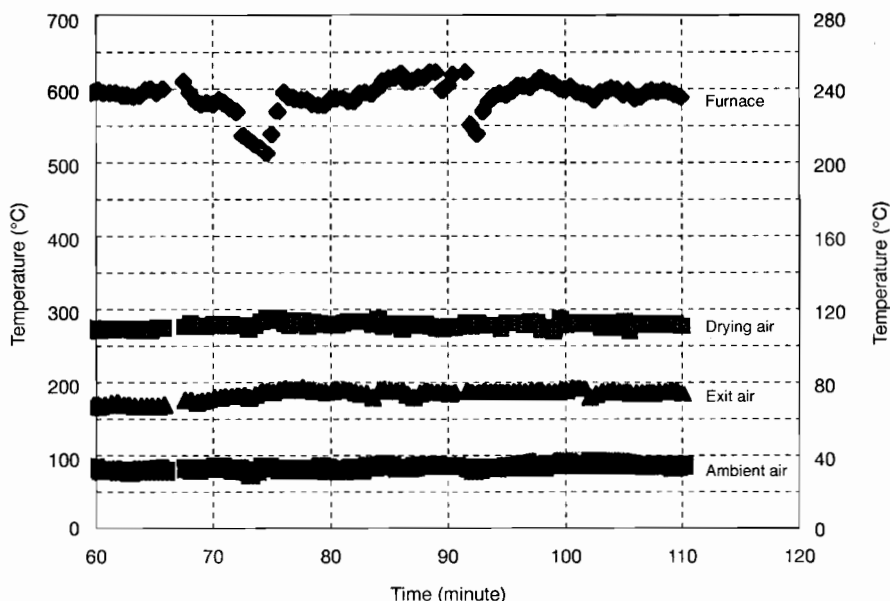


Figure 4. Temperature variation in 50 kg/hour pneumatic-fed rice husk furnace, October 1995, Song-Hau Farm.

Even with a $\pm 5^{\circ}\text{C}$ temperature variation, the furnace was considered stable. Rice husk consumption was 45–55 kg/hour.

The head rice recovery was analysed at UAF laboratory. It was comparable to shade drying. No difference in milled rice whiteness could be seen with the naked eye. No parboiling effect was noticed.

Experiment with maize

A batch of 400 kg of maize at 24% m.c. (w.b.) was dried in two passes with 30 minutes of cooling between passes. A drying temperature of 130°C was used. The capacity for one pass was 1200 kg/hour. The final moisture content after two passes was 16.3% (w.b.). While further experiments need to be made to optimise the dryer operation with maize, it can be safely conjectured that this fluidised-bed dryer can operate as a continuous-flow dryer, using much less space than a columnar dryer.

Drying cost

The drying cost was estimated based on the data and assumptions given in Table 2.

In terms of kg of water removed, the calculated drying cost is US\$0.044/kg H_2O . The drying cost is near the limit acceptable to farmers in the Mekong delta. Taking into account the short time needed to remove excessive moisture, the dryer is likely to be adopted from an economic viewpoint.

Table 2. Estimate of drying cost using the fluidised-bed dryer.

| Item | Data |
|---|--|
| Capacity | 1 t/hour (31% m.c. (w.b.) to 21%) |
| Investment | 70000000 VND ^a (US\$6400) |
| Life | 4000 hours (= 5 years \times 40 days/year \times 20 hours/day) |
| Interest rate | 23% per year |
| Electricity consumption (total) | 15.5 kWh/hour |
| Electricity price | 780 VND/kWh |
| Rice husk consumption | 50 kg/hour |
| Rice husk price | 100 VND/kg |
| Labour | 3 person.hours/hour |
| Labour rate | 5000 VND/person.hour |
| Cost component (Cost/hour = cost/tonne) | VND |
| Depreciation and repairs | 20000 |
| Interest | 10000 |
| Electricity | 12000 |
| Rice husks | 5000 |
| Labour | 15000 |
| Total | 62000 VND/t = US\$5.60/t |

^a During October 1995, ca 11000 Vietnam dong (VND) = US\$1.

A desk comparison of oil and paddy husks as the energy sources indicated costs per kg of paddy of US\$0.00355 for oil and US\$0.00046 for paddy husks in reducing moisture content from 31 to 21%. Thus, it can be projected that using oil would incur a heating cost seven times higher than with paddy husks.

Conclusions

For paddy with very high moisture of over 30% (w.b.) harvested during the wet season in the Mekong delta of Vietnam, fluidised-bed drying has shown positive preliminary results technically. The calculated drying cost is reasonable under the economic conditions of Vietnam.

Further work is in progress to enhance technical operations, and further reduce the drying cost.

Acknowledgments

The work reported here is part of the activities of ACIAR Project 9008 in Vietnam. Thanks are extended to the Australian Centre for International Agricultural Research for financial support; and to King Mongkut's Institute of Technology Thonburi, Thailand for technical support.

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Rice-husk Gasifier for Heat and Electricity Production for Small to Medium Mills

G. Vaïtilingom*

MORE than one billion people around the world are concerned with the production of some 500 Mt of paddy on 150 million ha of land. Since the husk surrounding the kernel of rice accounts for about 20% by weight of the paddy, about 100 Mt of rice husk are available. Although some of these rice husks are used for fuel or for other purposes, most of the residues are disposed of by burning or dumping. In most rice-growing countries, rice residues represent one of the largest potential fuel supplies for biomass energy projects (Mahin 1990). Each tonne of paddy generates about 200 kg of husks, the energy content of which is about equal to that of 60 L of fuel oil.

Use of Husks in Rice Mills

In medium-sized and large mills (processing more than 2 t of paddy/hour) rice husks are commonly used. Parboiling mills typically use steam generated with husks for both parboiling and drying. Where parboiled rice is not produced, steam is used from husk-fired boilers in steam engines or turbines for mechanical power and electricity generation.

In small to medium mills, the use of heat from rice husks is possible if electricity is available from a diesel plant or the grid to run the fans of heat exchangers. However, most of the commercial equipment and systems for the production of mechanical and electrical power from rice husks is suitable only for use in larger mills.

Most of the husks are available in small quantities at tens of thousands of small mills. In developing countries, the great majority of the rice mills are small mills processing paddy at a rate of less than 1 t/hour, and with an energy requirement of around 20 kWh per tonne of paddy. This is where there is strongest interest in small rice-husk gasifiers.

Rice-husk Gasification for Small and Medium Mills

Gasification could provide energy for drying and for electrical power. The major part of the gases could feed a gas engine to run the electric motors of the mill and of the gasifier itself; the remaining gases may provide enough heat for drying.

With the support of FAO, much research has been done to improve the design of gasifiers. Very few small units are available commercially at present. The main problems are the bulk density of rice husks, the high ash content (15–20%), and the characteristics of the ash (92–95% silica). These characteristics impose severe requirements on the design of gasification systems using rice husks (Vaing 1989).

Major Technical Problems of Husk Gasification

To provide the power needed for a small to medium-size rice mill processing paddy at 1 t/hour, the gasifier must burn husks at a rate of at least 100 kg/hour. This means that feed of husks to the gas generator must be almost continuous. To avoid slugging problems internal temperature must be controlled. Because of the high volume of ash it must be removed during operation with no contact allowed with atmospheric oxygen. The gas produced contains particulates, soot, tars, and moisture which must be removed before use in burner or engine. There are gasifiers able to produce gas continuously but they often fail because of inefficient cleaning units. Because of the low calorific value of the gas produced, high flow rates are needed to feed burners or engines. Even in the largest cleaning units the dirty gases have only some tens of seconds to be cooled, dried, cycloned, filtered, and purged of tars and, unfortunately, some tars do not condense at tropical ambient temperatures.

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A New Gasifier Design for Small and Medium Mills

To overcome the difficulties associated with gasifying rice husks, CIRAD—which has much experience in gasification of wood or agricultural wastes (coco-nut husks and shell, cotton stalks, peanut shells, briquettes, etc.)—has worked for several years to develop a new concept in rice-husk gasification.

A throatless gasifier with air inlet control has been designed. It is a downdraft gasifier with automated husk feeding and ash removal. Husks are fed by a screw conveyor to the air-sealed top of the gasifier. The air inlet is controlled by two series of nozzles. Ash is removed through a very simple water-sealed conveyor.

The cleaning unit consists of an air-gas cooling system, a collector for small ash, a wet scrubber with high flow-rate of water, a turbine and, finally, a paper filter. The scrubbing water passes through a cooling system, a procedure that is very important for the efficiency of the unit. Most of the soot and tars are collected in a large tank where they are concentrated and from which they can be easily removed for further processing. Cooled water is also injected into the turbine to improve the centrifugation of soot, particulates, and the remaining tars which are pushed into the tank with the help of the pressure delivered by the turbine. Pressured gases are able to pass through the very efficient paper filter. Low-pressure cooled and cleaned gases are finally available both for engine operation and for use in a very simple gas burner.

During the operation of the gasifier, the cycles of ash removal and husks feeding are controlled by off-the-shelf electric timers.

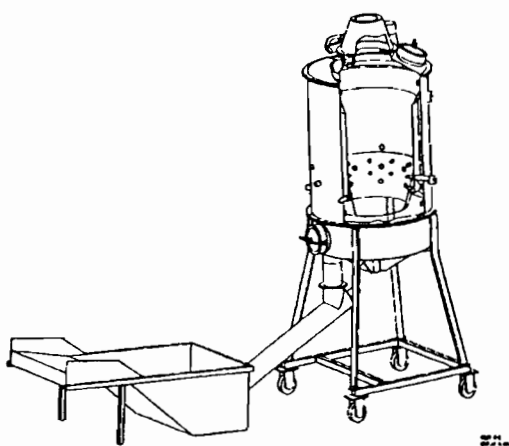


Figure 1. Section of the CIRAD gasifier.

In a version of the gasifier producing 150 m³ of gas per hour, the total power needed by the electrical devices to run the gasifier is 5 kW, which consumes 10–15 kg of husks, i.e. about 10% of the total consumption per hour.

Table 1. Typical composition of gas produced by small- to medium-scale rice-hull gasifier.

| Gas | Percentage of total |
|-----------------|------------------------|
| H ₂ | 8.7 |
| CH ₄ | 2.5 |
| O ₂ | 4.3 |
| N ₂ | 51.8 |
| CO ₂ | 12.2 |
| CO | 20.5 |
| Energy value | 4440 kJ/m ³ |

This gasifier was designed to be able to produce 75–150 m³ of gases per hour, with an average energy value of 4.2 MJ/m³. Table 1 gives typical gas composition. Special care was taken in the design to ensure it used technologies no more sophisticated than encountered in a small or medium-size mill. This allows for local manufacture of such units, which are adapted for mills processing paddy at a rate of 0.5–1 t/hour (Vaïtilingom 1993).

Conclusions

Most of the commercial equipment and systems for the production of heat and mechanical and electrical power with rice husks are suitable only for use in large mills. In small to medium mills, processing less than 1 t of paddy per hour, gasification could provide energy for drying and for electrical power. A gasifier scaled for small and medium mills and designed and built using technologies appropriate to such mills could be of interest and its cost would be attractive if it were locally made. The market for such a gasifier comprises tens of thousands of rice mills in many developing countries.

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Rice Drying Technology in China

Zhao Simong*

Abstract

The characteristics of rice drying in China are discussed. There are three main high-temperature drying systems and one low-temperature drying system being applied. Rotary grain dryers have the features of simple structure and homogeneous drying effect. Two types of fluidised-bed grain dryers are used in China, namely single-bed dryer and multi-bed dryer. A new type of rice dryer which has come into use in China is the concurrent-counterflow dryer. The low-temperature drying system is the so-called mechanical ventilation equipment. The technological characteristics of high- and low-temperature dryers are discussed and analysed. To avoid reducing the quality of rice during drying, the correct way to select parameters relating to the drying technology are also covered.

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Heat and Mass Transfer in Grain Bunks of Arbitrary Shape

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Abstract

Bulks of grains may assume an infinite number of shapes. Although the equations that govern the rates of heat and mass transfer in such bulks are independent of the size and shape of the grain bulk to be modelled, the choice of a numerical solution procedure depends on the geometry of the grain bulk. This paper describes a method of transforming the shape of a grain store into one that has a simple geometry such as a cube or right circular cylinder. Works are cited that detail how the method has been used to simulate heat and mass transfer phenomena in two- and three-dimensional grain bunkers, rail cars and hopper bottomed grain stores.

THE shapes and sizes of bulks of stored grain are quite arbitrary. For example, when a hopper bottomed farm silo is filled with grains, the upper surface of the grain usually forms a cone. The grain bulk therefore has the shape of a right cylinder, capped with a cone of grain and with an inverted cone on its base. Although the bulk of grain may be axi-symmetric the temperature of the outer surface varies both spatially and temporally as a result of solar radiation which varies with time. Regions of the silo facing away from the equator are generally cooler than those facing towards the equator. The system must therefore be considered to be truly three-dimensional. Similarly, when a grain storage shed is filled with grain, a ridge of grain usually forms under the inloading conveyor, and at each end of a ridge truncated cones form, that may intersect retaining walls. Again we have a bulk of grain that must be treated as a three-dimensional entity.

Grain storage technologists are often concerned with manipulating the ecosystem within bulks of grain, and this requires some understanding of the processes of heat and mass transfer that occur within them. The equations that govern these processes are well established (Thorpe 1996a,b), and they apply to grain bulks of any shape or size. To solve them one must specify the appropriate initial and boundary

conditions such as the temperature and moisture content of the grain as it is loaded into the store, and the temperatures of the surfaces of the store, say. The equations are usually solved numerically using some form of finite difference approximation. When the grain store has a simple shape such as a cube or a right cylinder, or a triangle (see Nguyen 1987) the solution is quite straight forward because an orthogonal finite difference mesh can be forced to coincide with the boundaries of the store. In this situation, the finite difference forms of the boundary conditions are quite easily imposed (see Singh et al. 1993). In the case of a peaked bulk of grain placed in a hopper bottomed silo, coincidence of the nodes of a finite difference mesh with the boundaries of the grain is unlikely. This problem may be overcome by using interpolation and other techniques outlined by Carnahan et al. (1969), or the geometry of the grain store may be mathematically transformed into a simple shape, such as a right cylinder or a cube as described by Singh and Thorpe (1993b). Casada and Young (1994) have used the transformation method to simulate heat and mass transfer in agricultural commodities transported in rail cars. The latter approach has the advantage that it is quite general, and easily programmed. A disadvantage of the method is that it cannot readily account for the case when one linear dimension of a grain bulk tends to zero, such as when a bulk of grain rests on a floor. At the point of intersection of the grain and the floor the height of the bulk is zero.

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In this paper we shall describe the method of grid transformation which has the above mentioned advantage of generality, and outline how it has been applied to the problem of moisture migration in two- and three-dimensional peaked bulks of grains, and the aeration of a hopper bottomed circular silo.

Grid Transformation

The aim of grid transformation is to map the shape of the grain store into a simple shape on which it is possible to impose an orthogonal finite difference grid. Figure 1 shows how Singh and Thorpe (1993a) transformed the cross-section of a bulk of grain, as may be found in a grain bunker, into a square.¹

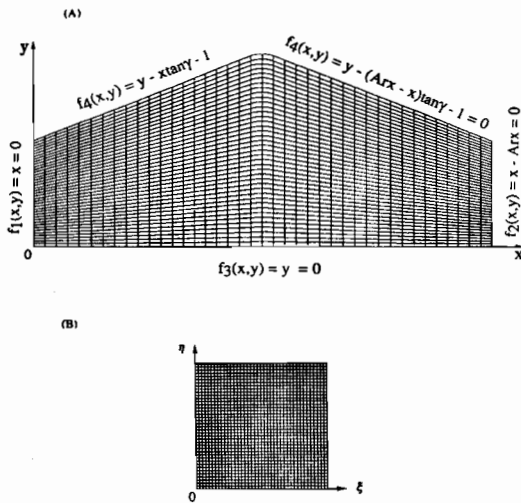


Figure 1. The transformation of the cross-section of a grain storage bunker into a square.

The geometry and its associated fields, such as grain temperature and moisture distributions, are described in terms of (x,y) coordinates, whereas the transformed system is described in terms of the dimensionless (ξ,η) coordinates. In the case under consideration, the relationship between the two coordinate systems is

$$\xi = \frac{x - f_1(x,y)}{f_2(x,y) - f_1(x,y)} \tag{1}$$

¹ A diskette containing an annotated FORTRAN computer program that models moisture migration in a two-dimensional peaked grain store is available from the author (GRT) free of charge.

$$\eta = \frac{y - f_3(x,y)}{f_4(x,y) - f_3(x,y)} \tag{2}$$

By the chain rule of differentiation we are able to write

$$\frac{\partial T}{\partial x} = \alpha_1 \frac{\partial T}{\partial \xi} + \alpha_2 \frac{\partial T}{\partial \eta} \tag{3}$$

and

$$\frac{\partial T}{\partial y} = \alpha_3 \frac{\partial T}{\partial \xi} + \alpha_4 \frac{\partial T}{\partial \eta} \tag{4}$$

in which

$$\alpha_1 = \frac{\partial \xi}{\partial x}, \alpha_2 = \frac{\partial \eta}{\partial x}, \alpha_3 = \frac{\partial \xi}{\partial y}, \text{ and } \alpha_4 = \frac{\partial \eta}{\partial y}$$

We can similarly write a laplacian as

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \beta_1 \frac{\partial^2 T}{\partial \xi^2} + \beta_2 \frac{\partial^2 T}{\partial \eta^2} + \beta_3 \frac{\partial^2 T}{\partial \xi \partial \eta} + \beta_4 \frac{\partial T}{\partial \xi} + \beta_5 \frac{\partial T}{\partial \eta} \tag{5}$$

in which

$$\beta_1 = \alpha_1^2 + \alpha_3^2, \beta_2 = \alpha_2^2 + \alpha_4^2, \beta_3 = 2(\alpha_1 \alpha_2 + \alpha_3 \alpha_4)$$

$$\beta_4 = 2\left(\frac{\partial^2 \xi}{\partial x^2} + \frac{\partial^2 \xi}{\partial y^2}\right), \beta_5 = 2\left(\frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2}\right)$$

The equations that govern heat, mass and momentum transfer in the physical (real) domain are easily transformed into a domain with the simple geometry by substituting into them equations 3, 4 and 5. As an example, let us consider the thermal energy balance presented by Thorpe (1995), i.e.

$$\frac{\partial T}{\partial t} + t_{pi} \left(\frac{\partial(uT)}{\partial x} + \frac{\partial(vT)}{\partial y} \right) + \left(t_{mx} \frac{\partial T}{\partial x} + t_{my} \frac{\partial T}{\partial y} \right)$$

$$= t_{pd} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + t_r + t_l \tag{6}$$

which in the transformed domain becomes

$$\frac{\partial T}{\partial t} + t_{pi} \left(\alpha_1 \frac{\partial(uT)}{\partial \xi} + \alpha_2 \frac{\partial(uT)}{\partial \eta} + \alpha_3 \frac{\partial(vT)}{\partial \xi} + \alpha_4 \frac{\partial(vT)}{\partial \eta} \right)$$

$$+ \left(t_{mx} \left(\alpha_1 \frac{\partial T}{\partial \xi} + \alpha_2 \frac{\partial T}{\partial \eta} \right) + t_{my} \left(\alpha_3 \frac{\partial T}{\partial \xi} + \alpha_4 \frac{\partial T}{\partial \eta} \right) \right)$$

$$= t_{pd} \left(\beta_1 \frac{\partial^2 T}{\partial \xi^2} + \beta_2 \frac{\partial^2 T}{\partial \eta^2} + \beta_3 \frac{\partial^2 T}{\partial \xi \partial \eta} + \beta_4 \frac{\partial T}{\partial \xi} + \beta_5 \frac{\partial T}{\partial \eta} \right) + t_r + t_l \tag{7}$$

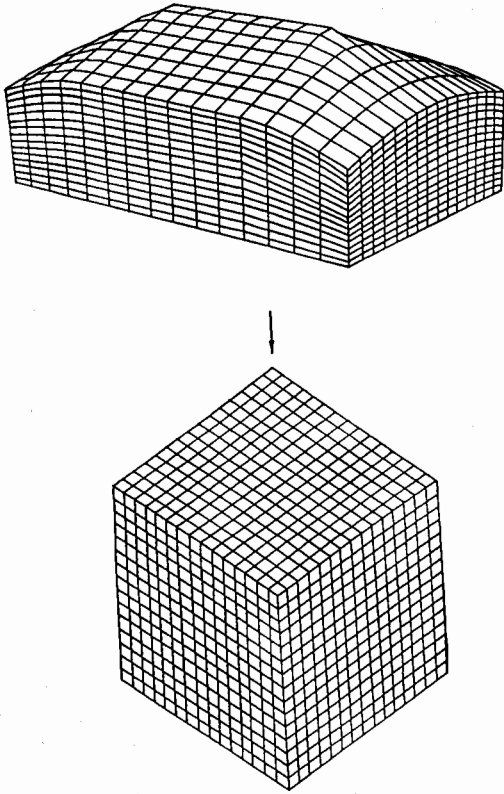


Figure 2. The transformation of a peaked bulk of grain into a cube.

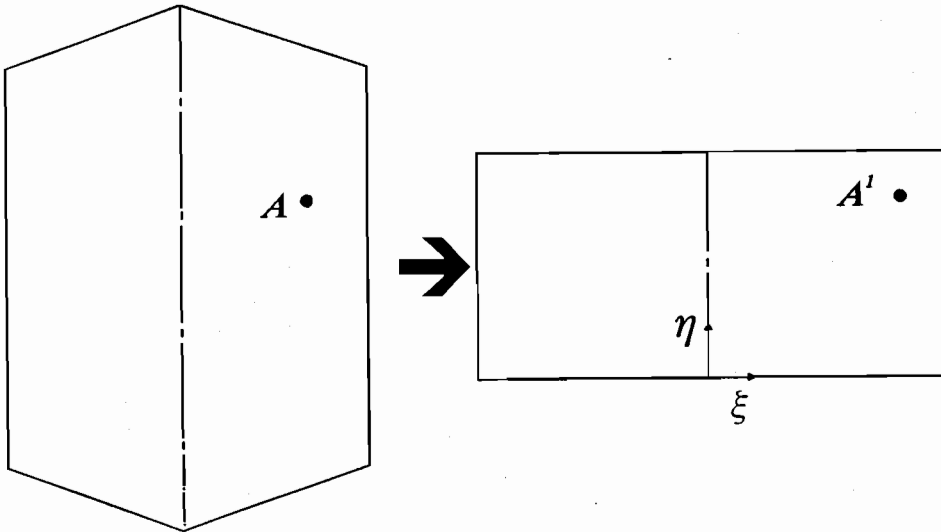


Figure 3. The transformation of a peaked bulk of grain contained in a hopper bottomed silo into a right cylinder.

This equation is discretised using the method described by Thorpe (1995).

The method is readily extended to three-dimensional systems as described by Singh and Thorpe (1993b) who modelled moisture migration in grain bunkers. In this case, the grain bulk was transformed into a cube, as shown in Figure 2. More recently, Thorpe (1996c) has transformed a hopper bottomed silo into a right cylinder, as indicated in Figure 3. Figure 4 shows the calculated pressure distribution generated by a linear aeration duct placed along one side of the base of the silo. Needless to say, the air flow pattern is three-dimensional in nature, and Thorpe (1996c) shows how the pressure distribution may be used to model heat and mass transfer phenomena in the such silos.

Conclusions

Bulks of grain assume an infinite variety of shapes. This paper describes a convenient method of modelling heat and mass transfer phenomena that occur in such bulks. The method is based on transforming the geometry of the grain store into a simple one which readily accommodates an orthogonal finite difference mesh. The method has been applied to grain bunkers with a uniform cross-section, three-dimensional grain bunkers, rail cars containing agricultural produce and to hopper bottomed cylindrical silos.