In-bin Grain Drying Systems

R. Driscoll and G. Srzednicki*

Abstract
The main categories of in-bin dryer systems are reviewed. For Southeast Asian conditions, research on in-store dryers is discussed, as a component of a two stage drying system for maximum quality preservation and reduced drying cost. Limitations for paddy and maize exist, requiring management of the system to obtain these benefits. Examples of adoption of in-store drying in conjunction with first stage dryers are presented.

In-bin drying is drying grain in bins commonly used for grain storage. It is divided into two main classifications: low-temperature (air heated by less than 6°C), and high-temperature drying (air heated to over 50°C).

The objectives of drying are the same as for any other unit operation: to process maximum product at minimum cost whilst maintaining adequate quality. Drying is not able to improve the product quality. Its value is in arresting spoilage by controlling water activity within the product. There are further advantages in reducing the bulk required for transport and in preparing paddy for milling.

Concepts

If drying is performed at an excessive rate, the grain becomes susceptible to fissuring, due to the creation of moisture gradients within the product. These gradients may be due to the drying process directly, caused by too high a drying air temperature, or more commonly to exposure of the product to a readsorption environment. Fast dryers operate at high temperatures, and will tend to cause fissuring if the grain is not allowed to temper. For maize and paddy, once the moisture is reduced below a certain moisture content (m.c.) corresponding to a significant drop in water activity below 1), high-temperature drying becomes inefficient and will tend to cause cracking.

For this reason, forms of drying in two stages have been developed around the world. The basic strategy is to use high temperatures while the grain is still elastic, and low temperatures for removing bound water from the product so that stresses have time to relax within the product. The introduction of two-stage drying to Southeast Asia will be the main topic of this paper.

Theory

In-bin drying in Australia

The technique of in-store drying was adopted early in the history of Ricegrowers’ Co-operative Limited, a farmer cooperative in New South Wales, Australia which grows and markets its own grain, and to which over 98% of the farmers belong. In the 1950s, the American technology of in-store drying was adopted, accompanied by conversion from bag handling to bulk handling, in order to solve problems of high paddy moistures and sun cracking (Bramall 1986). The procedure allowed paddy to be harvested at around 21% m.c. (wet basis, w.b.), and then dried in-store to below 14% w.b. for storage and milling.

In-store drying was effective because the ambient conditions in Australia were suitable for this form of aeration, and no supplemental heating was required. Initially, radial bins with mesh walls were used, but based on research at the University of California, ducts at the bottom of the bulk were adopted. Later, under-floor aeration was installed to allow easier access for transport and loaders.
Over the years the system has been refined, with layer filling, computer controlled bins, supplementary heating, computer-based harvest systems and computer models of drying.

In-bin drying in the United States

Background

In the United States forms of in-bin drying have been used for many decades (since the 1950s), with great success for the maize industry in the central states. Design is based on studies of weather conditions. Experience has shown that both design and careful management are crucial to the success of the system. The main difficulties with implementation in the USA have arisen from the increased time before the grain is dried, increasing the risk of deterioration. Sufficient good quality air must be available at grain collection time to ensure that spoilage can be prevented.

Since in-store drying operates at near ambient conditions, minor changes in ambient conditions can have large effects on the drying rate, and thus careful research is required to ensure that adequate good quality air is available in any year for accomplishing the grain drying objective, which is basically to move the drying front through the grain mass before deterioration is significant in the top layer of the grain. This research has been conducted by the United States Department of Agriculture and by various universities. Much of the research has been conducted by means of computer simulation.

As a result of this research, areas of the United States have been zoned according to the aeration conditions required for full bin drying (Chung et al. 1986). Schedules for different locations are specified, so that the grain is quickly cooled after harvest and to make sure that the grain receives sufficient aeration for drying. Various methods of operating the drying bins have been developed (see introduction). Systems for preventing overdrying and top to bottom moisture gradients, loading and unloading, and rewetting of the inlet layers have been developed.

System types

The appeal of in-bin drying is that it saves on equipment costs, by allowing the same bin used for storage to double as a dryer. In all cases air is passed slowly through the bin of grain, picking up moisture as it does so. Careful design is required to ensure that all of the grain in the bin is adequately dried.

The main types of in-bin drying are (Brooker et al. 1992):

- full bin: bin is filled with grain, and dried, cooled, aerated and stored in the same bin
- full bin with stirring, allowing more uniform grain treatment
- layer filled bin, in which grain is dried in successive layers, new grain being added as the previous layer is dried
- on-floor batch in-bin, used for drying a batch of grain and occasionally for cooling as well, in a method similar to the flat-bed dryer used in Asia
- recirculating, in which grain at the bottom of the bin is picked up by auger, swept to the centre and then augured to the top of the bin, where it is respread, allowing the grain to be recirculated for more uniform treatment and reduced airflow resistance
- dryeration, a specific technique in which grain is dried at high temperature in a bin, to within 2–3% m.c. (w.b.) of the actual final moisture required, then transferred hot into a tempering bin. After the drying stresses have been allowed to equalise, the grain is then cooled using ambient air, the stored heat removing the final 2–3% moisture. This gives a high quality grain with low susceptibility to breakage.

Various other more sophisticated forms also exist. For Southeast Asian conditions we are concerned to find the simplest, most robust drying system for the severe climatic conditions, and so the main concern of this paper is in-store drying, which is typically full-bin drying at low temperature.

Stir augers

Stir augers are devices for vertical mixing of the grain. The augers rotate slowly around the bin, taking 1 to 2 days to complete a circuit (Intong 1995). Two major problems with in-bin dryers are solved by the use of stir augers: moisture gradients caused during drying, and compaction of lower layers by the upper, resulting in decreased airflow.

Stir augers are not often recommended for Southeast Asia due to the high initial cost, wear on the augers from paddy, and lack of supplier support, even though simulation studies indicated a clear benefit (Intong 1995). Other problems are increased mechanical damage to the grain, and reduced air thermal efficiency.

Recirculation of air

Studies on air recirculation were conducted using computer simulation at the University of New South Wales. The results showed that recirculation at about 90% was of marginal benefit for the last period of full-bin drying (after the drying front has reached the top of the bed so that the exit air relative humidity starts to decrease). This is because air comes to equilibrium with the wettest grain in an in-store drying system, and so the system naturally has a high thermal efficiency – there is no need to recirculate the air. In general, air recirculation never justifies its installation costs for in-store dryers.
Dehumidification

Air recirculation becomes more effective if dehumidification is used. Moisture from the bin exit air is extracted by cooling the air, and then re-enters the grain to do additional drying. Again this system has not been applied to any great extent to tropical countries because it depends on cooling equipment and has a high investment cost. An alternative to dehumidification is using a desiccant bed. Due to their cost these have only been applied to high value food products and pharmaceuticals.

Recirculation of grain

Recirculation of the grain on the other hand has proven to be a more successful option, for example:
• partial drying in one bin followed by auguring to a second bin; and
• auguring grain from the bottom of the bin to the top. This allows tempering, mixing and repacking of the grain to reduce pressure drops. This technique has been applied in Thailand for aerating grain.

In-bin drying in Southeast Asia

Mechanical dryers were promoted in the late 1970s throughout the region, but were generally poorly chosen and unsuitable for humid tropical conditions. Many were rejected by the end users. The first appropriate technology was developed by Dr Dante de Padua, and this was the flat-bed dryer, still extensively used 30 years later. The wet season harvest was increasing the drying load, and many international research agencies were contacted to look for possible solutions. The Australian Centre for International Agricultural Research, through its Postharvest Research Program led by Dr Bruce Champ, suggested studying the application of in-store drying to tropical countries.

The research method adopted was as follows:
• set up research teams in each country;
• study paddy and other grains to determine key thermophysical properties, such as isotherms, thin-layer drying rate, specific heat etc.;
• construct a deep bed drying model (Dung et al. 1981);
• obtain detailed information on harvest practice, times, and weather conditions;
• feed these through the simulation to determine suitable drying conditions;
• test recommendations at three levels in all countries, pilot plant (1–5 t), commercial trials (up to 500 t) and full scale implementation.

This has now been done in the Philippines, Thailand, Malaysia, and Vietnam. Crops studied under the research program include peanuts, soybeans, maize, mung beans and, of course, paddy. A typical recommendation for an in-store drying system would depend on location, grain type, harvest moisture, loading and unloading equipment, and existing storage structures, but a typical recommendation for a humid tropical climate would be a grain height of 4 m, maximum receival moisture of 18% (w.b.), supplementary heating of a few degrees, and an air speed of more than 6 m/min.

Reports on the field trials are available as follows:
• in-store drying commercial trial in Malaysia (Srzednicki and Driscoll 1992);
• field trials in Thailand (Soponronnarit et al. 1994);
• Current research topics are:
• improved loading and unloading techniques;
• first-stage drying;
• computer control systems;
• development of small scale in-store dryers;
• quality measurement.

Real bin effects

Computer modelling of drying systems has been of immense benefit in predicting their performance. Three forms of models have competed for dominance:
• The near-equilibrium model, in which thermal equilibrium between the air and the grain is assumed to exist at all points in the bed at all times. Examples are Thompson et al. (1986), Soponronnarit and Chinsakolthanakorn (1990), Driscoll (1986b), and Jindal and Siebenmorgen (1994).
• The non-equilibrium model, in which heat transfer and mass transfer are modelled at all points in the grain mass. As with near-equilibrium models, the drying problem is treated as one-dimensional. Examples are Dung et al. (1981) and Bakker-Arkema et al. (1974).
• The three-dimensional model, in which differential transport equations are used to model moisture and heat movement. An example is Thorpe (1994).

Each approach has advantages and disadvantages, but except for ideal situations, none could claim an accuracy of greater than 10%. The advantages of the near-equilibrium approach are:
• computation is fast;
• real-bed effects can be easily included—a wide range of these effects has now been modelled, and so can be included in the drying system;
• graphical presentation of results can be integrated with the drying program.

The real-bed effects have turned out to be important factors. Some of the effects now included are heat losses through side walls, respiration, pressure energy regain, and quality models. Factors still needing inclusion are grain settling, better thin layer drying models and stress relaxation models.

The near equilibrium model of the University of New South Wales (UNSW) team (Driscoll 1986b) also includes:
• economic analyses for Southeast Asian countries,
• recirculation,
• grain freezing and sublimation drying,
• dehumidification and heat pump operation,
• effect of fines on pressure,
• bin design tools,
• thermophysical data presentation,
• aeration module for developing drying strategies quickly for specific weather conditions,
• four quality models,
• user-friendly (mouse and button) interface,
• a wide range of products,
• weather module for analysis of weather data.

Inclusion of these factors has become necessary to make the simulations robust design, optimisation, and strategy-development tools.

Application

Application to Southeast Asia

The previous section shows that there are many potential in-bin drying solutions. The system which has been most widely researched in Southeast Asia is in-store drying, in which grain is dried in bins (either full or using layer filling) and then stored in the bins under aeration until required for milling. The equipment required is:

- a storage bin able to sustain a small air pressure (i.e. mesh or hessian walls are not suitable, but brick, concrete and timber are)—note, however, that in Thailand bags of grain with a tarpaulin lining have been successfully used!
- a fan and air ducting of suitable size,
- underfloor or ducted above floor aeration (underfloor, the preferred option for handling, may be too expensive for existing sheds, or too difficult to install, especially in the old timber sheds),
- a loading and unloading system,
- a burner if simulation determines that supplementary heating is required,
- a trained operator,
- a weather station capable of determining ambient temperature and relative humidity (for example, an operator with a wet and dry bulb thermometer),
- temperature sensors placed at known heights (1 m separation) in the grain mass are of great benefit in determining the performance of the system,
- a programmable controller is of benefit in improving the control and reliability of the system.

The minimum quantity of grain for returning an economic benefit under Southeast Asian conditions appears to be about 100 t per load. If grain (paddy and maize) is harvested above 18% m.c. (w.b.) in humid climates, a system for reducing the grain moisture to below 19% is required; for example, first-stage dryers (hence this system is often called two-stage drying). The drying time is about 10–15 days for the operating conditions recommended for tropical climates.

Examples of applications

The earliest attempts were mismanaged trials using USA Butler bins. Caking and yellowing considerably damaged the reputation of in-bin drying for Southeast Asian conditions. The fan sizes chosen for these bins were an order of magnitude too small for the tropics. Some rough trials on shallow beds were also made by the Northern Philippines Grain Complex.

Kongskilde bins use a form of in-bin drying (a radial orientation), and have proven very successful due to careful training of operators. Although a safe solution, we do not believe that this design exploits the full potential benefits of in-store drying.

In Thailand adoption at Kittisak Wattana mill was on the basis of improved grain quality if aeration of existing bulk bins was implemented. The success of this implementation lead to the installation by the owner of new storage bulk bins designed on in-store drying principles, allowing the owner to purchase paddy at a higher moisture content. Three other mills have tested the system but had major handling problems, suggesting correct design and management are crucial to the success of in-store drying. Several other complexes are testing in-store drying, including Chachoengsao, Tron, and a range of small-scale mills. Seminars by Soponronnarit and collaborators have stimulated interest amongst millers in this technology. The Department of Agriculture will evaluate two-stage and in-store drying with a view to wider adoption by the Thai milling industry.

In the Philippines, NAPHIRE has developed an in-store dryer of 66 t capacity, currently being used by Dayap Multipurpose Development Cooperative, located near Los Baños (Calauan, Laguna) (Tumambing et al, 1995). This is designed to run in conjunction with the NAPHIRE fast dryer, and has a pneumatic loading system. It has operated for only one season, but this was successful with paddy dried to an average of 13.5% in 43.5 hours at P40/tonne. At the same site and time sun drying cost P100/t (mainly in labour cost). The in-store-dried rice was of good quality. A second trial in the dry season gave similar results. No yellowing occurred. Personnel training was an important component of this field trial. In-store technology was used for several years by the NFA and was tested by the Northern Philippines Grain Complex. NAPHIRE now plans to build additional units in 1995–96.

In-store aeration using computer control has been implemented at the BERNAS mill in Kangkong, Malaysia.

Adoption has been more rapid in Vietnam, moving from testing to implementation in one year.
of the dryer is strongly affected by local weather conditions.

Attempts have been made to in-store dry in one stage in Southeast Asia. Our own computer studies at the University of New South Wales indicate that this is not a suitable or sensible option for humid tropical climates for moistures above 19%, as the air speed required to prevent deterioration of the upper layers is too high for economic operation. Thus, two-stage drying is the preferred option.

Conclusions

In-store drying is a slow drying technique which saves on capital costs by combining the role of dryer and storage bin. Research on its implementation in Southeast Asia has shown that it has an important role to play in the complete drying picture on the basis of producing high quality grain at low cost. Successful adoption is dependent on good design, good management practices, and a large scale of operation for second stage drying. Design of the dryer is strongly affected by local weather conditions.

References


Renewable Energy Sources for Grain Drying

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Abstract

This paper examines existing and potential systems which enable the use of renewable energy sources for grain drying. The scale and distribution of process drying operations in Asia is reviewed and the various mechanisms for obtaining heat and power from renewable resources are identified. The need to focus on smaller-scale systems is highlighted. An alternative system to traditional sun drying, which has been implemented in Indonesia, is described. This involves use of auxiliary solar heating to provide technical and financial benefits in performance of commercial, induced-draught mechanical-dryers. Available biomass resources are considered together with the implication for supply and pre-treatment. Some specific types of biomass burners are described including various options for rice husk combustion. The significance of combustion control on rice husk ash quality for effective by-product use is examined through work that has been carried out with co-workers in Sri Lanka. Combined heat and power (CHP) options are reviewed including recent work on a technology under development by the Natural Resources Institute. This will use low cost vehicle turbocharger components as elements of an indirect biomass-fired heat exchanger/air turbine cycle for power systems at around 100 Kw_e output and with scope for small-scale CHP applications.

There are various technical options for application of renewable energy to grain drying. The extent to which they have been or may be adopted is ultimately dependent upon economic factors, but a number of important issues can be identified. Use of renewable energy will generally reduce running costs compared with fossil fuel usage. It may also give a degree of operational independence, e.g. from price variations or from supply restrictions. Environmental benefits can be associated with the use of renewable energy at local and/or global levels but these may not be easily measured in cash terms. This paper will aim to present options that may be considered for specific applications rather than make overall recommendations. These options can be grouped into basic routes for either heat or power. Also, as some opportunities exist where technical options for combined heat and power need to be considered, these are examined.

Heat—sun drying, solar assisted mechanical, biomass fuelled

Grain drying is in fact already largely achieved through renewable energy by direct sun drying. This is a topic on which there has been substantial study and it was covered in detail at an FAO conference in 1993 (Bakker-Arkena and Suhargo 1993). A step beyond this basic technology is solar drying and the technology associated with this and the variety of systems appropriate to postharvest processing has been dealt with elsewhere in a way that fully covers the particular aspects relating to grain drying (Brenndorfer et al. 1985). A particular system of solar assisted mechanical drying for rice will be described in this paper by way of an example.

The other important renewable route to provision of heat is the combustion of biomass fuels. These need to be considered in terms of basic fuel characteristics and pre-treatment. Technology exists for major renewable biomass fuels such as wood and straw; also, there are routes for combustion of particulate forms of biomass that may be considered separately. The specific issues relating to the combustion of rice husks are important.

Power—renewable electricity, direct biomass-fuelled power systems

Grain drying as a process operation invariably requires power input. This may be solely human labour but, for the purpose of this paper, consideration is given to needs for shaft-power, either for direct mechanical application or for electricity production. Electricity may be generated locally or centrally, so theoretically hydro-power or wind-power come into this category. Electricity once produced by renewable

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means is available to generate shaft power and/or heat. More emphasis will be placed in this paper on routes involving thermal processing, e.g. biomass, since this creates also waste heat, thereby offering scope for combined heat and power. The various routes to heat and power are illustrated by Figure 1.

Need for focus on smaller-scale requirements

Knowledge of the size distribution of process operations such as grain drying is important when considering potential for use of renewable energy sources. For rice, the major grain crop of Asia, some information has been collated in Table 1.

From this information it is evident that by far the majority of rice processing is currently performed in small-scale operations. For this reason the emphasis in this paper is on the smallest scale of processing technology that can be envisaged. Normally this excludes the direct application of commercial systems from fully industrialised countries although there is often scope for scale-down. Also, in order to keep costs down the use of local equipment and construction must be maximised.

Solar-Assisted Mechanical Drying

A prototype paddy drying system utilising both solar energy and waste heat from an engine with a throughput of 10 t/day of paddy was designed, constructed, and evaluated at a rice mill in West Java, Indonesia. The dryer is inherently similar to a conventionally heated flat-bed dryer, except that the air for drying is partially heated by a solar collector. There are three separate components to the dryer, all of which are located within an open-sided building, as shown in Figure 2. The components are:

(a) a bare plate solar collector integral with the roof of the building;

(b) a combined engine and fan unit collectively termed a moisture extraction unit (MEU); and

(c) two drying bins positioned adjacent to each other with a common manifold duct.

Solar collector

The cost of a solar collector can be minimised if it can be incorporated within the roof of a building. There are many versions of roof-type collectors; the basic distinguishing feature between them being the configuration of the flow path of the air through the collector. The bare plate collector is the simplest version of the roof-type collector. The air flows from one end to the other of a rectangular duct, the upper side of which is the blackened metal roof sheeting (absorber), and the lower side a thin wooden ceiling fixed to the roof timbers. The performance of bare plate collectors with corrugated iron sheeting as the absorber has been investigated (Trim and Fish 1996). The orientation of the building and the slope of the roof are the major factors determining the heat output from the collector. So that the collector surface is exposed to insolation throughout the day, the dryer building should be constructed with its longitudinal axis running from east to west. It is generally the case that the roof slope should be such as to maximise the angle of incidence of insolation upon the roof and hence the heat output from the collector during the peak harvesting period.

Table 1. Size distribution for rice processing in some Asian countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>Nos vs capacity, tonnes paddy/hour</th>
<th>&lt;1</th>
<th>1-2</th>
<th>2-3</th>
<th>&gt;3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indonesia</td>
<td>About 2 million registered ‘large’ rice mills with average production of about 1000 t/year; unknown number of smaller mills.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malaysia</td>
<td>Nos vs capacity, tonnes paddy/hour</td>
<td>99</td>
<td>107</td>
<td>66</td>
<td>107</td>
<td>379</td>
</tr>
<tr>
<td>Philippines</td>
<td>Nos vs capacity, tonnes paddy/hour</td>
<td>n.a.</td>
<td>108</td>
<td>35</td>
<td>22</td>
<td>19</td>
</tr>
<tr>
<td>Thailand</td>
<td>Nos vs capacity, tonnes paddy/hour</td>
<td>20,000</td>
<td>1,500</td>
<td>102</td>
<td>42</td>
<td>17</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>Nos vs capacity, tonnes paddy/hour</td>
<td>&gt;0.5</td>
<td>0.5-2</td>
<td>≥2</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5,600</td>
<td>1,600</td>
<td>n.a.</td>
<td>&gt;7,000</td>
<td></td>
</tr>
</tbody>
</table>

Paddy produced (1993) — 2680 x 10^3 (total rated capacity — 2640 x 10^3 t/hour)

a Girard 1993
b Palipane, personal communication, 1995
Figure 1. Routes for conversion of biomass or waste to energy.

Figure 2. Schematic of paddy dryer. For illustration, air is shown passing up through the right-hand bins and (separately) down through the left-hand bins.
Moisture extraction unit (MEU)

The MEU consists of an axial-flow fan directly driven by a diesel engine, as used with conventional flat-bed dryers. Before passing through the fan the air flows over and around the engine block thereby absorbing the waste heat produced by the engine. The MEU is positioned centrally within the fan house at one end of the building. It is connected via a canvas coupling and flange to the manifold duct. The exhaust gases from the engine are piped outside the fan house to avoid contamination of the paddy with combustion by-products.

Drying bins

The two bins, positioned next to each other with a common side wall, are each internally 10 m long, 3 m wide, and constructed of rendered brick. The drying chamber within each bin is 1.25 m deep with a floor of perforated metal sheeting. Each bin is fitted with five moveable plywood covers through which paddy is loaded, and six unloading ports in the outer side and end wall of the bin.

The flow of air into a bin is through ports, either into the plenum chamber (for the up-flow of air through the bed of paddy), or into the top of the drying chamber (for down-flow of air). Air is exhausted from the bin through the loading ports or through outlet ports along the bottom of the side wall of the bin. The common side wall between the bins contains cross-over ports to permit the flow of air from one bin to the other.

Operating principles

Air is drawn through the solar collector and into the fan house by the MEU and thence into one or both of the drying bins. There are three different modes of operation:

(i) air is blown through the lower inlet ports into the plenum chamber of one (or both) bin and flows up through the paddy, exhausting through the loading ports;
(ii) with the loading ports closed, air is blown through the upper inlet ports into the top of the bins before passing down through the paddy and exhausting through the outlet ports;
(iii) air is blown into the plenum chamber of one bin, up through the paddy, then—as the loading ports are closed—through the crossover ports into the second bin, before passing down through the paddy and exhausting through the outlet ports of the second bin.

Changing from one mode to another is carried out simply by opening and shutting the requisite ports and covers. Three labourers are required for this changeover operation.

Conclusions

It was found that, in addition to the dryer providing increased drying capacity compared with sun drying, the solar-dried paddy provided both an increase in milling yield and rice of improved quality for which premium prices were paid. Fuel consumption of the dryer was 29% less than that of a conventional flat-bed dryer. Financial analysis showed that the improvements in milling yield and rice quality more than compensated for the high fixed and variable costs of the dryer, with a payback period of three years.

Biomass

General considerations

Fuel characteristics and pre-treatment

The physical form in which biomass fuels are supplied can vary considerably, and moisture content, particle size, and bulk density, in particular, are important basic parameters. The consequence of variation in these properties can have far-ranging effects on the energy density of the material. These effects are illustrated by the data in Table 2 where typical values are used to calculate the volume of fuel with the same energy as that contained in 1 m$^3$ of fuel oil, for straw and wood as available in different forms.

Straw lying in the field is normally recovered by baler and this greatly reduces its volume. An alternative process of in-field compaction to produce compressed wafers has been developed to a prototype stage and will further increase the density. Still higher density pellets are also available from various types of compaction equipment.

With wood, the range of materials that must be considered includes forestry waste, i.e. logging residues, thinnings, etc., through to timber as either unseasoned (green) or seasoned (air dried), and in solid or chipped form. Also, there are various forms of processing wastes, and such materials can be specially converted into fuel pellets using compaction equipment.

It will be seen from Table 2 that the various forms of wood and straw have energy contents from 4 to 100 times lower than fuel oil. This points to the importance of collection and supply of such fuels. These and the broader aspects of material handling are key elements in the supply of such materials as economic alternatives to fossil fuel.

Apart from the physical properties mentioned, complete fuel characterisation requires measurement of the key variables such as: calorific value; volatile matter; thermogravimetric analysis; ash content; moisture content; elemental analysis; and fusion temperature. Requirements for these measurements are appropriate sampling techniques and sufficient analyses to provide statistical means and averages.
Table 2. Energy content for straw and wood as fuel.

<table>
<thead>
<tr>
<th></th>
<th>Moisture (wet basis) (%)</th>
<th>Bulk density (t/m³)</th>
<th>GCV (GJ/t)</th>
<th>Energy content (GJ/m³)</th>
<th>Vol of fuel (1 m³ oil) (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straw</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loose (unchopped)</td>
<td>15</td>
<td>0.03</td>
<td>13.5</td>
<td>0.4</td>
<td>102</td>
</tr>
<tr>
<td>Loose (chopped)</td>
<td>15</td>
<td>0.06</td>
<td>13.5</td>
<td>0.8</td>
<td>50</td>
</tr>
<tr>
<td>Large bales</td>
<td>15</td>
<td>0.15</td>
<td>13.5</td>
<td>2.0</td>
<td>21</td>
</tr>
<tr>
<td>Compressed wafers</td>
<td>15</td>
<td>0.30</td>
<td>13.5</td>
<td>4.0</td>
<td>10</td>
</tr>
<tr>
<td>Pellets</td>
<td>12</td>
<td>0.50</td>
<td>14.0</td>
<td>7.0</td>
<td>6</td>
</tr>
<tr>
<td>Wood</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest waste</td>
<td>50</td>
<td>0.3</td>
<td>8.4</td>
<td>1.7</td>
<td>24</td>
</tr>
<tr>
<td>Unseasoned timber (solid)</td>
<td>50</td>
<td>0.8</td>
<td>9.3</td>
<td>7.4</td>
<td>6</td>
</tr>
<tr>
<td>Unseasoned timber (chips)</td>
<td>25</td>
<td>0.35</td>
<td>15.0</td>
<td>5.2</td>
<td>8</td>
</tr>
<tr>
<td>Seasoned timber (solid)</td>
<td>50</td>
<td>0.65</td>
<td>9.3</td>
<td>6.0</td>
<td>7</td>
</tr>
<tr>
<td>Seasoned timber (chips)</td>
<td>25</td>
<td>0.23</td>
<td>15.0</td>
<td>3.5</td>
<td>12</td>
</tr>
<tr>
<td>Process waste (solid)</td>
<td>12</td>
<td>0.63</td>
<td>16.5</td>
<td>10.4</td>
<td>4</td>
</tr>
<tr>
<td>Process waste (chips/ etc)</td>
<td>12</td>
<td>0.12</td>
<td>16.5</td>
<td>2.0</td>
<td>21</td>
</tr>
<tr>
<td>Pellets</td>
<td>12</td>
<td>0.7</td>
<td>16.5</td>
<td>11.5</td>
<td>4</td>
</tr>
<tr>
<td>Coal</td>
<td>9</td>
<td>0.85</td>
<td>28</td>
<td>24</td>
<td>1.7</td>
</tr>
<tr>
<td>Oil</td>
<td>0</td>
<td>0.9</td>
<td>46</td>
<td>41</td>
<td>1</td>
</tr>
</tbody>
</table>

After collecting such data it is necessary then to substantiate the conclusions from analysis by means of proving trials in which practical aspects need to be assessed. Such considerations are smoke levels, ease of handling, boiler fouling, ash clinker, particulate emissions, silo blockage, and fuel delivery preparation.

Straw and wood burners

Development work in the U.K. to realise the potential use of both straw and wood as commercial fuel has been similar in that in both cases there has been initially a systematic attempt to identify any existing coal-burning equipment which could be readily adapted to alternative fuel firing. This has initially involved proving trials on such equipment with wood or straw either as an alternative fuel or in a co-firing mode. Various systems were examined and, for both straw and wood, the same general conclusion was reached—namely that the different fuel characteristics of coal were such that while straw and wood could be burnt with varying degrees of success in coal-fired plant there was usually a marked down rating of the plant, especially when using fixed or moving grate systems. Thus, unless for some reason the existing equipment of this type was grossly oversized for its duty there was no real point in attempting 100% alternative fuel replacement.

Some success was found in trials with straw co-firing by means of suspension conveying of chopped straw into the furnace in a secondary combustion air stream. One option for 100% fuel substitution with straw was potentially more successful and involved burning in a cyclone furnace such as can be retrofitted to shell boilers.

With wood, the same range of options was essentially examined but while there was a rather better performance in the various grate systems the same general conclusion about severe downrating was reached. The prospect of lean phase conveying for co-firing is not available for most forms of wood, apart from sawdust or wood shavings.

The general conclusion reached was that specialised burners are required for these materials. Extra investment can, however, often be minimised by retrofitting of cyclone combustors. Most of the straw currently used for on-farm fuel purposes is burnt in low-technology, manually stoked whole bale burners of which there is a full range of U.K. equipment available. These are typically in the range of 20 to 300 kW thermal output.

For larger ratings, such as are commonly required in industrial and commercial applications there are various arrangements that are available or under development. One development funded by the U.K. Department of Energy was a boiler unit capable of taking whole large Hesston bales for direct feed to a furnace. Other examples of commercial systems are available in Denmark. There are also possibilities for high-capacity utilisation of these materials and these include fluidised-bed combustion and suspension firing of particulate materials for co-firing with pulverised coal.
Particulate biomass combustion

Types of particulate biomass

Work was done by the Natural Resources Institute (NRI) to identify the quantities of key biomass residues that occur in particulate form in Asia since it was considered that these materials were more amenable to design of generic equipment. Information was gathered for rice husk, coconut shells, palm shells, sawdust, and peanut shells (Table 3). This showed the high amounts of rice husk, particularly in Asian countries. Also, some information on the quantities of grain residues available was derived which showed how widely this could vary depending upon the crop yield (Table 4).

Following this background study, work was focused on burner development for rice husk and sawdust combustion (Robinson 1991). The rice husk combustion system developed under this program is described below.

Table 3. Estimated production of biomass residues in Asia (NRI 1991).

<table>
<thead>
<tr>
<th>Country</th>
<th>Rice husk</th>
<th>Coconut shells</th>
<th>Palm shells</th>
<th>Sawdust</th>
<th>Peanut shells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>'000 t</td>
<td>'000 t</td>
<td>'000 t</td>
<td>'000 t</td>
<td>'000 t</td>
</tr>
<tr>
<td>Afghanistan</td>
<td>4,561</td>
<td>13</td>
<td>69</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Bangladesh</td>
<td>2,815</td>
<td>28</td>
<td>84</td>
<td>208</td>
<td>49</td>
</tr>
<tr>
<td>Bhutan</td>
<td>17</td>
<td>12</td>
<td>89</td>
<td>1,740</td>
<td>29.0</td>
</tr>
<tr>
<td>Burma</td>
<td>15,982</td>
<td>735</td>
<td>4,566</td>
<td>1,257</td>
<td>26.5</td>
</tr>
<tr>
<td>China</td>
<td>7,929</td>
<td>1,740</td>
<td>3,026</td>
<td>1,135</td>
<td>26.5</td>
</tr>
<tr>
<td>Indonesia</td>
<td>394</td>
<td>28</td>
<td>1,581</td>
<td>152</td>
<td>3.6</td>
</tr>
<tr>
<td>Iran</td>
<td>31</td>
<td>28</td>
<td>718</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Iraq</td>
<td>349</td>
<td>7</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kampuchea</td>
<td>1,271</td>
<td>1.4</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Korea DPR</td>
<td>1,557</td>
<td>1.7</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Korea Rep</td>
<td>243</td>
<td>0.3</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laos</td>
<td>384</td>
<td>270</td>
<td>2,338</td>
<td>1,089</td>
<td>16.8</td>
</tr>
<tr>
<td>Maldives</td>
<td>468</td>
<td>1.5</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mongolia</td>
<td>1,780</td>
<td>26.0</td>
<td>214</td>
<td>181</td>
<td>4.2</td>
</tr>
<tr>
<td>Nepal</td>
<td>436</td>
<td>263</td>
<td>118</td>
<td>274</td>
<td>6.4</td>
</tr>
<tr>
<td>Pakistan</td>
<td>3,618</td>
<td>53</td>
<td>190</td>
<td>498</td>
<td>11.6</td>
</tr>
<tr>
<td>Philippines</td>
<td>57</td>
<td>0.1</td>
<td>498</td>
<td>118</td>
<td>2.8</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>3,137</td>
<td>61</td>
<td>194</td>
<td>4.5</td>
<td></td>
</tr>
</tbody>
</table>

Burner development for rice husk

Initial design and development work was conducted at the NRI laboratories in the U.K. on a pilot unit. Results obtained from the pilot unit were promising and the project progressed to the field-testing stage. The test site chosen was a commercial rice processing mill in Sri Lanka. The mill, Richard Pieris Agricultural Enterprises Limited, situated in the rice growing region of Anuradhapura, has a milling capacity of 2 t/hour and a parboiling capacity of 4 t/hour. The rice husk combustion system was installed and connected to the mill's boiler to raise steam for associated parboiling operations. The system was scaled-up from 250 kW thermal to 750 kW thermal to meet an increased heat demand and, with a few other modifications which included an external ash collection chamber, it has worked very well for the past 4 years. Another unit was installed at the Rice Processing Research and Development Centre (RPRDC), Anuradhapura for experimental use with a fluidised-bed paddy drier. The field demonstration trials were carried out in collaboration with RPRDC.
Table 4. Crop residue production under different yield situations (NRI 1991).

<table>
<thead>
<tr>
<th>Yield</th>
<th>Country</th>
<th>Crop yield (t/ha)</th>
<th>Crop: residue ratio</th>
<th>Residue yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>Low Guinea</td>
<td>0.9</td>
<td></td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Medium LDC Average</td>
<td>3.6</td>
<td>1.75</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>High China</td>
<td>5.1</td>
<td></td>
<td>8.9</td>
</tr>
<tr>
<td>Wheat</td>
<td>Low Tunisia</td>
<td>0.7</td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Medium LDC Average</td>
<td>2.0</td>
<td>1.75</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>High Egypt</td>
<td>3.5</td>
<td></td>
<td>6.1</td>
</tr>
<tr>
<td>Maize</td>
<td>Low Zaire</td>
<td>0.8</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Medium LDC Average</td>
<td>1.9</td>
<td>2.5</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>High Egypt</td>
<td>4.6</td>
<td></td>
<td>11.5</td>
</tr>
<tr>
<td>Sorghum</td>
<td>Low Niger</td>
<td>0.3</td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Medium LDC Average</td>
<td>1.2</td>
<td>2.0</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>High Mexico</td>
<td>3.4</td>
<td></td>
<td>6.8</td>
</tr>
<tr>
<td>Millet</td>
<td>Low Chad</td>
<td>0.4</td>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>Medium LDC Average</td>
<td>0.7</td>
<td>2.0</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>High China</td>
<td>1.7</td>
<td></td>
<td>3.4</td>
</tr>
<tr>
<td>Groundnuts</td>
<td>Low Zimbabwe</td>
<td>0.2</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Medium LDC Average</td>
<td>1.0</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>High Egypt</td>
<td>1.9</td>
<td></td>
<td>4.4</td>
</tr>
</tbody>
</table>

A diagram of the system is shown in Figure 3. The burner operates on the principle of suspending the husk in air during combustion. This helps ensure an intimate mix of air with the husk and facilitates complete and efficient combustion. The furnace is sized to provide a heat output of approximately 900 MJ/hour (equivalent to approximately 250 kW thermal) with a husk consumption of 60 kg/hour at 10% moisture content. The burner is suitable for both unbroken husk from a rubber huller or broken husk mixed with bran from a steel sheller. Ash can be collected in the furnace chamber or in an external ash collection chamber, depending on user requirements.

The temperature of the combusted gases can be maintained at around 1200°C, which allows effective heat transfer in any connected boiler or other system, such as heat exchanger for indirect air heating in a mechanical dryer. The furnace has a thermal efficiency of approximately 95%. Overall system efficiency largely depends on husk moisture content and heat exchanger efficiency—typical values are 60 to 70%. Flue gases vented to atmosphere contain no smoke and reduced ash emissions.

The components of the system comprise:

**Vibratory feed hopper.** A 0.3 m³ capacity vibrating hopper of basic design (see Fig. 3) is fitted with a small out-of-balance motor to produce a steady vibrating action. At the bottom of the hopper an adjustable gate is installed to regulate the flow of husk. The system operates satisfactorily and delivers a steady flow of husk.

**Injector feeder.** This device, developed by NRI (Tariq and Lipscombe 1992), is used in conjunction with the vibratory feed hopper described above. It consists of two different diameter pipes connected in series to the outlet of the fan. The flow of air through the contraction caused by the smaller diameter pipe produces a region of negative pressure in the larger diameter pipe. Connected to the larger pipe is an inlet pipe and funnel to feed the husk. Husk and air is sucked into the pipe by the negative pressure.

**Paddle fan.** A mild-steel centrifugal paddle fan of 380 mm paddle diameter, driven by a 0.6 kW electric motor and capable of delivering air up to 13 m³/min at NTP is used for the development trials. The optimal excess air value for the efficient combustion of husk is approximately 80%, equivalent to a delivery of approximately 350 m³/hour of air at a husk feed rate of 60 kg/hour.

**Brick-built furnace.** The furnace is built with four layers of brick to provide necessary durability and insulation. An arched roof avoids the need for lintels and other supporting structures associated with flat roof construction. The furnace chamber is partitioned to direct the travel of husk in an up-and-down path, thus increasing its residence time. A central partition divides the furnace into a primary combustion chamber and ash collection chamber. Access to each chamber is by insulated hinged doors. Husk is blown into the lower region of the primary combustion chamber and the hot gases exit the upper region of the ash collection chamber.
Heat exchanger system. The system should have a thermal rating to at least match the furnace gross thermal output of 900 MJ/hour (equivalent to 250 kW thermal) and be capable of withstanding hot combustion gases at a temperature of up to 1200°C. The corresponding mass flow of combustion gases at the typical operating conditions described above is approximately 500 kg/hour. While the ash collection chamber will trap the majority of the ash, a small but significant quantity will be entrained in the combustion gases. It should be noted therefore that some ash deposition, fouling, and wear of heat exchanger surfaces are likely to occur, the extent of which will largely depend on the type and design of the heat exchanger. This needs to be considered in the maintenance schedules for the various applications of the system.

Where rice-processing mills adopt this system, various heat and/or power applications are possible either with steam, hot water, air, or a thermal fluid as the heat transfer medium. In addition, the furnace system could be used in conjunction with an existing solid-fired system to supplement energy needs. For example, the husk burner could be connected to a furnace operating on fuelwood. In this case, fuelwood consumption could be reduced at a rate proportional to the amount of husk burnt. On a typical 8 hour/day husk burner operation, 280 days a year, some 110 t of air-dry fuelwood could be saved annually.

Work has been carried out by NRI and RPRDC on this furnace to define the limits of operations for feed rates and excess air levels on this equipment. An experimental design was established and a matrix of tests completed for three rice-husk feed rates of 50, 85 and 120 kg/hour, and for four sets of excess air values from 20% to 200% inclusive. Systematic ash quality evaluation from these trials was investigated based upon X-ray diffraction techniques. This has shown the control conditions necessary for optimal rice husk ash (RHA) characteristics (K.B. Palipane, unpublished data, 1993).

Rice husk combustion

Use as a by-product

Disposal of rice husk is a problem sometimes addressed by indiscriminate dumping and burning. However, rice husk is increasingly being burnt with recovery of heat and/or power. Combustion results in a high yield of RHA which contains around 95% silica. This silica is potentially a valuable by-product, depending on its quality specification and, in particular, the extent to which it has retained its non-crystalline or amorphous characteristic. NRI has examined methods to devise equipment and operational conditions for combustion of rice husks in a manner capa-
ble of supplying energy for industrial processing and of providing a high grade rice husk ash for by-product use as a silica source.

Commercial initiatives for use as a building material component are widespread and well documented. While there is a potentially large market for such products they attract only a low market price. Other applications of RHA, many of proven commercial status, include: insulation uses, refractories, reinforcing agents and fillers, fertilizers, filter mediums, and as a silica chemicals raw material (Beagle 1978). These generally demand lower volumes but a tighter specification and thus have the potential to attract a higher market value.

Quality control of the RHA is the main problem with existing combustion systems and even with RHA use in cement, probably the least sensitive to changes in quality, serious product specification problems exist. Greater control over the combustion process allows closer specification of RHA properties.

The crystalline properties of silica in RHA are strongly affected by the temperature of formation and the duration of heating. There is also evidence that the level of impurities has a significant influence upon change of crystalline structure with temperature. This subject has been comprehensively reviewed recently (James and Subba Rao 1992).

The particular amorphous crystalline characteristic of silica in rice husk which derives from its role in plant structure can be maintained only through the combustion process if the temperature of combustion is kept low. Precise temperatures vary but above 500°C it seems some significant degradation will commence. However, it appears that even at temperatures of over 1000°C the amorphous structure will be retained provided the ash is quickly cooled. With increasing temperature the silica structure progressively changes into cristobelite, tridymite, and quartz crystalline forms.

A high degree of amorphous structure of silica is known to give it a high reactivity in terms of its use for cement. The amorphous structure is very porous and has high surface area so this also gives a high activity for chemical treatment and in absorption. In general, silica in this condition has far more potential for commercial utilisation than mineral sources of silica which are characterised by higher temperature crystalline forms.

Types of system

Techniques for thermal processing of rice husk to derive energy and/or provide RHA for subsequent use are commercially available. Some key systems are described below with an emphasis on potential small-scale processing.

Brick incinerators. The status of these devices has been detailed through reports (Smith and Tait 1989; Cook 1985). Development of these low-cost incineration systems has been limited to the use of RHA in cement production. Through this work the importance of thermal processing techniques upon the physical properties of the ash has been established and although for this application there is some latitude on product quality it has been found necessary to draw-up a specification for RHA masonry cement. RHA for use in cement requires grinding in ball mills and the energy input for this operation is minimised with a high degree of amorphous silica in the ash. The time for milling may vary by a factor of seven and, being an energy intensive operation, it is a key consideration for process economics of RHA cement production.

Traditional step-grate boilers. Inclined-step grate boilers are the traditional design for rice husk burning. There are various configurations and the range has been fully described (Beagle 1978). In normal use these units burn the husk at high temperature (above, say, 700°C) under conditions which result in the formation of crystalline ash. In general, it appears that the ash from traditional step-grate furnaces does not retain an amorphous characteristic.

Fluidised-bed combustion. Fluidised-bed combustion of rice husk is a technique with intrinsic potential for producing amorphous ash since it enables low combustion temperatures. This route was applied for a large capacity application in USA in 1976 of 7.5 t rice husk/hour. Also work on 2 t/hour rice husk, fluidised bed, combustion units is reported to have been carried out in India and Australia (Cook 1985). NRI work on a fluidised-bed combustion and carbonisation test rig for particulate biomass indicates a need to evaluate 1/2–1 tonne/hour systems for application in developing countries (Hollingdale et al. 1990).

Vortex gasifiers. Renewed emphasis has been placed on biomass thermal gasification in recent years since it can provide a high conversion efficiency route to derive shaft power from the thermal energy of biomass. In some preliminary collaborative work by Biomass Energy Services and Technology (BEST) and the National Building Technology Centre (NBTC) attempts have been made to generate a consistent amorphous ash from a 30 kg/hour rice husk feed rate vortex gasifier (Hislop 1991).

Pyrolysis/steam gasification. The Indian Institute of Technology has advocated a thermal processing route for conversion of rice husk to process recovery of silica from the ash. The technique proposed is controlled pyrolysis followed by steam gasification of carbon present in char and it is said to be economically attractive at a system capacity of 6 t/day rice husk feed with output of 120 kW electrical power and 1 t/day silica (Grover 1992).

Brick suspension burner. Suspension burning with waste heat recovery offers good temperature control of combustion and commercial systems at 6 t/hour
feed rates are available. The NRI low-cost brick-built suspension burner operates at 180 kg/hour rice husk feed rate and produces 33 kg/hour of ash. Ash analyses by X-ray diffraction has indicated a high amorphous content though it is recognised that more work is required to establish design and operation procedures which would ensure a consistent ash to a market specification (D. Nicholas, pers. comm., 1995).

Implications of ash quality

In order to develop an understanding of the benefits that would accrue from a burner that provided a high grade amorphous rice husk ash, cost models were examined based on experience of the NRI 180 kg/hour furnace in Sri Lanka. The results show that the production costs of rice husk ash are considerably lower if a heat production component is included into the project. Without heat production the cost of producing 1 t of ash is US$32 compared with $18 if heat production is included. This production cost of RHA in Sri Lanka is only about one eighth of the price ex-factory in Europe, without considering the value of the by-product heat. Clearly this is attractive but it is essential that the quality specifications be examined to establish a full comparison for its use. Also, there are particular aspects in relation to various products as described below.

Cement. Production cost models for lime/RHA cements have been published for India (Cook 1985). Production costs were competitive with standard cement at $60/t when the rice husk was costed at a nominal figure of $1/t. However, it was projected that if the rice husk costs increased due to its use for fuel, as has now happened in some situations, then production costs for these processes would become too high for the product to compete. In 1992 the estimated production cost of 1 t of cement using RHA in Sri Lanka was between $37 and $45, depending on the quality. This compared with bags of Indian cement being sold then at a price equivalent per tonne of $106.

Refractories. By far the most important end market for refractories is the iron and steel industry. Trade has indicated that there is a European market for 20,000 t/year of RHA for refractory bricks in the cement and steel industry. The kiln products, glass, and non-ferrous metals industries represent most of the remaining demand for refractory products and will have a smaller but nonetheless important impact. In the context of a specific developing country it has to be examined which among the above industries are prevalent in the national economy. Only a preliminary assessment of potential cost savings from use of RHA in refractory bricks has been possible. This suggests that use of local RHA in Sri Lanka as a substitute for an imported raw material could reduce production costs by 25–30%.

*Sodium silicate.* Sodium silicate solutions (water glass) have properties similar to those of organic colloids like gums and resins, but with the advantage of being colourless, odourless, heat resistant, and of becoming insoluble. The major uses of sodium silicate are connected with its adhesive, wetting, binding and detergent properties. It is widely used in the washing soap industry to improve the foaming capacity of soap. In addition, water glass is used to putty glass and china, to conserve foodstuffs such as eggs, to impregnate paper, and as a fire-resistant paint.

Indian workers have analysed low cost routes to sodium silicate from RHA (Andiappan 1981). These schemes relate to low outputs in the region of 1–3 t/day and the method of production described is primarily intended for sodium silicate used for soap making. It is not clear that they could meet raw material specifications for major users of sodium silicate but the route involved does benefit from the use of amorphous silica and is therefore of interest in the context of this exercise. Thus, 1 t of sodium silicate produced in India would cost $148. In November 1992, the trade list price of sodium silicate on the international market was between $456 and $978/t depending on the quality and quantity.

*Other products.* Sodium silicate is a raw material for production of a range of products with a variety of overlapping uses, known generically as fumed silica and precipitated silicates. Other silicon products that have been identified and which could be derived from amorphous rice husk ash are silicon carbide, silicon tetrachloride, silicone nitride, silane, semi-conductor/metallurgical grade silicon, and catalyst supports. Each involves particular production techniques which have been ascertained to varying degrees. In these, the use of a high quality amorphous silica is generally advantageous.

Prospects for product development

RHA cement does not offer a high value-added use of RHA since the price must be competitive with standard cement products. Previous studies on RHA cement have been re-examined and it is concluded that this product is only likely to be profitable with large-scale operations.

Sodium silicate and RHA refractory bricks are two products to which more attention should be applied. These would sell at higher cost than RHA cement and might be produced more cheaply than comparable products not using RHA as a raw material. Reduced production costs would arise partly from the fact that RHA is an intrinsically cheap material but also from the technical benefits stemming from the amorphous structure.

In view of the market potential for commercial products from RHA there should be further development of a furnace/combustor that provides energy in
association with a high grade RHA. Parallel work on quality assessment of RHA is required. Experimental work should be focused on low cost and simple construction which makes it directly applicable to less-developed countries (LDCs).

Market evaluation for silica production derived from RHA should be extended and commercial collaborative links established with a view to encouraging joint venture operations in LDCs where a degree of added-value production can be anticipated.

**Small-scale combined heat and power**

**Energy balance in a typical rice-processing mill**

A summary of the energy requirements of a typical 2 t/hour rice processing mill with a husk-fired steam boiler is shown diagrammatically in Figure 4. It is assumed for this mill that mechanical drying is not required on receipt of paddy and that the paddy is stored in sacks—therefore there is no energy input at these stages.

Based on the following assumptions:
(a) 2 t/hour rice processing mill, generating 440 kg/hour of rice husk
(b) husk net calorific value of 13.5 MJ/kg
(c) furnace efficiency of 90%; boiler efficiency of 65%
(d) overall steam turbine or steam engine efficiency of 6%.

A Sankey diagram of a theoretical combined heat and power installation is shown in Figure 4.

The electrical power of 99 kW available approximately matches the mill’s electricity requirement of 95 kW, made up of 20 kW for drying and 75 kW for milling. Should, in practice, there be an excess of electricity production, consideration could be given to earning revenue by supplying the grid, if connected, or adjacent/local industry or local community. In the event of insufficient electricity production to meet the mill’s demand, grid electricity or some other form of back-up generation system would be required.

The energy from the turbine or engine exhaust steam broadly matches the energy requirement for the hot water soaking, parboiling, and drying operations—2792 MJ in the exhaust steam versus 2700 MJ required.

**Gasifiers**

The equipment available for the steam-based systems at this scale is limited and suffers from low efficiencies and high costs which are of the order of GBP1600/kWe (during October 1995, ca65 pounds sterling (GBP) = US$1). In many countries, considerable effort over a long period has been put into the development of a marketable gasifier system. Despite this effort such systems have not progressed beyond prototype stages. The efficiencies of the small-scale gasifier systems can be of the order of 20%. The projected costs of gasifier based systems are in the range GBP1600–12000/kWe. The gasifier systems also suffer from the drawback that they produce a noxious by-stream of liquor and tar. This con-

![Figure 4. Energy flow in a combined heat and power system.](image-url)
sists of known carcinogens and disposal costs for this material are not often included in the financial appraisal of these systems. Due to the large water content and toxic nature of the wood tars/liquor, their disposal costs are not likely to be insignificant. The waste heat in the gasifier systems is of low grade. Furthermore, the gasifier systems are not very tolerant of changes in the fuel properties. The biomass fuels are inherently of variable quality, particularly their moisture and ash content are determined by the ambient conditions, harvesting, and handling history. Therefore, a need exists for a small-scale power generation system which can provide efficiencies comparable to the gasifier systems, is cheaper, and does not suffer from the drawbacks of the gasifier systems. The work described in this paper is an attempt to address this need.

**Indirect turbine**

Recent work by the NRI funded through the EU’s JOULE II Non-nuclear Energy program, has identified the attractiveness of energy cropping for power generation systems at around 100-300 kW for on-farm generation. Based on preliminary design studies an indirectly-fired gas turbine system was identified as a potentially attractive option at scales of around 200 kW. The commercial viability of this type of system is enhanced if operated in combined heat and power mode. In addition to on-farm systems, considerable scope for applications of a system of this size exists where biomass residues are available, as in small- to medium-sized processing industries. Such applications arise in both developed and developing countries and may include rice mills with drying and parboiling heat requirements.

Earlier studies on indirectly-fired turbine cycles have concentrated on large, high-efficiency systems which have necessitated the use of expensive materials for construction and/or sealed systems filled with gases such as helium. The systems investigated were based around turbines developed for direct firing. On the scale considered here, the approach is to focus on the economic viability and financial return of the unit—not simply to concentrate on higher efficiencies alone—since it has been shown that competitively priced electricity, from biomass, can be produced only from a system with low capital, operating, and maintenance costs; and high ‘availability’. Indirect-fired gas turbine offers a potential to meet both of these criteria as it uses clean air as a working fluid and is based on rotating turbo-equipment with inherently long service intervals and greater reliability.

The indirectly fired cycle has the potential to produce electricity at efficiencies of 20% at modest turbine inlet temperatures and low turbine pressures. In the past, aero-derivative engines have been used which are optimised for a high power to weight ratio and operate at high inlet temperatures. This has resulted in a requirement for heat exchangers made from ceramic materials. This project presents a new approach tailored to the requirements of small-scale stationary power generation under 500 kWc particularly for combined heat and power applications.

The technology will use low-cost turbine and compressor systems based on automotive turbo-charger technology. The thermodynamics of a number of variants of indirectly heated turbine cycles have been evaluated with realistic values for various component efficiencies. A cost-effective system with an overall efficiency of 20% is possible using a single heat exchanger instead of two; as normally associated with recuperative indirectly heated turbines. The size of this single heat exchanger is less than the combined size of a separate heat exchanger and recuperator. Also, a cycle operated in this mode encounters lower heat exchanger temperatures and operates at a lower pressure ratio (3-4). The combination of lower temperatures and pressures results in requirements for the materials of construction which can be met with stainless steel rather than ceramics or nickel-based alloys. The system is illustrated in Figure 5.

The following parameters were used in the calculations:

- Polytropic efficiencies of compressor and turbine: 0.85
- Effectiveness of heat exchanger: 0.85
- Pressure losses in the heat exchanger (for both hot and cold sides): 3% of inlet pressure
- Losses in gearbox and alternator: 10% of turbine net work
- Temperature at inlet of turbine: 750°C
- Temperature at outlet of combustor: 900°C
- Combustor losses: 5% of total heat input into the combustor
- Fuel:
  - Moisture content 25% (wet basis)
  - Ash content 1% (wet basis)
  - Gross calorific value 19 900 kJ/kg (daf basis)
  - Net calorific value 13 140 kJ/kg (as fired basis)

Most of the components for the proposed system are available but will require some modification and development work. The turbine, compressor, furnace, and low-temperature recuperator would be derived from existing technologies. However, there is a need for some development work on combustion systems to reduce potential fouling of the heat exchangers; on higher temperature heat exchangers and on turbo-machinery, especially the turbine side. Application of high-speed generator technology which has the potential for simpler control and to eliminate gearbox losses, is also to be investigated.
It is anticipated that a system could be developed which would cost less than GBP800/kWe when in production. Using this figure electricity from such a system could be produced at a break-even price of 5.6p/kWh (100p = 1GBP). This is based upon the following assumptions:

- Size of the system 250 kWe
- Installed cost GBP800/kWe
- Cycle efficiency 20%
- Use of thermal energy (450 kW at 1.8p per kW)
- Heat rejection from the system at 100°C

It is planned that an optimised prototype system will be designed and costed as the next stage of this work.

Acknowledgments

This work has been funded through the Renewable Natural Resources Research Programme of the U.K. Overseas Development Administration. The author also wishes to acknowledge the assistance provided by: Dr K.B. Palipane and his staff at the Rice Processing Research and Development Centre, Anuradhapura, Sri Lanka; and by Dr D. Nicholas, University of Greenwich, U.K.

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Non-conventional Grain Drying Technology

Francis Courtois*

Abstract

Drying is probably the oldest method for preparing grain for long-term storage. Many scientists are seeking to understand the underlying phenomena, the influence of drying on quality, and to optimise the design and/or control of industrial dryers. Many technologies exist (air drying, freeze-drying, steam drying, etc.) but most of them are restricted to specific products and developed countries. Some of them are designated 'non-conventional', mainly due to their high investment cost and the level of technology required. In most cases, they are not well suited to developing countries.

Many constraints have to be considered in developing countries when designing a dryer. Thus, the global optimisation of the drying operation requires advanced knowledge. Even the precise definition of the objectives of drying can be complex. Objectives are contradictory (e.g. energy efficiency is generally opposed to drying capacity). Quality and moisture content must also be considered. The complexity of the interactions between the different objectives is difficult to resolve, but the modelling approach can help here. The automatic control approach appears to increase the global performance of existing dryers. These tools can be invaluable to engineers and operators even if they are mostly used in laboratories.

DRYING is one of the oldest methods for enhancing the 'storability' of biological products. For cereal grains, we can say that it is the oldest and only solution applied. Depending on the level of industrialisation, the drying may be natural or artificial, or a combination of the two.

It is difficult to define what is a 'non-conventional' drying technology since what is conventional in Europe may not be so in Asia and vice versa. As we will discuss, non-conventional often means 'unacceptable cost'.

Our aim here is not to review unusual technologies for drying. Of more interest from our point of view is to focus on the physical goals and constraints of grain drying and then propose some solutions.

As we will see, drying involves many different products and goals, and is applied in so many technological environments that we need to use a general approach close to the level of microscopic phenomena.

First, we may say that we are all interested in optimising grain drying. That is, we want the drying to be inexpensive (investment and running costs), multipurpose, maintain grain quality, be under automatic control, etc.

We will focus on each goal in an endeavour to understand how to optimise the drying process.

Methodology

Dryer optimisation can be studied at three levels:

• The design level, if the dryer is not yet built. We need to make a choice between a diversity of technologies, materials, dimensions, etc.
• The set-up level, if the dryer already exists. We need to find the best setpoint to optimise the objectives.
• The control level during drying. We need real-time corrections of the setpoint to avoid perturbations and reduce the overall standard deviation in the outlet moisture content.

Whatever the level of optimisation we seek, the objectives remain the same. We need to define the objectives with precision, in terms of an equation.

Defining Objectives

Grain drying generally has several objectives. Figure 1 shows the most common ones. Each problem is specific and thus has a specific objective map. As can be seen, objectives may be contradictory. For example, maximising the product flow rate generally involves the highest energy cost.

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Figure 1. Drying objectives can be contradictory.

Since we are going to use some mathematics, we prefer to group all objectives in a single cost function \( J \):

\[
J = \int_{0}^{\text{total time}} \left[ a_1 (\text{energy cost})^2 + a_2 (\text{invest cost})^2 + a_3 (X_{\text{exp}} - X_{\text{obj}})^2 + \ldots \right] dt \tag{1}
\]

This cost function \( J \) has very general use. To fit particular objectives, we need to set the values of the \( a_i \) coefficients. Choosing these values is equivalent to finding the correct compromise between energy cost, quality, investment, etc. Note that the investment cost can be treated separately, since it is incurred before the dryer is operational.

This cost function is obviously an integral of time since none of the variables are constant. In particular the third term is subject to large variations and thus leads to consideration of automatic control as an optimisation solution.

Primary Objectives

Energy

First there are some physical limits to energy efficiency. When using air as a drying medium, the energy consumption is at least 2.3 MJ (550 kCal) per kilogram of water, the latent heat of vaporisation. Dryers in western countries generally have energy efficiencies of 700–1200 kCal per kilogram of water, and it would be quite difficult and expensive to reduce this energy requirement.

Generally, good energy efficiency is associated with higher investment costs (more complex construction) and may thus be incompatible with constraints encountered in the developing countries.

It can also run counter to the drying capacity, since the highest energy efficiency is obtained with cribs in western countries at a very low cost but a very low production capacity.

How is energy lost during drying? As we will see later, exhaust air is rarely saturated and thus still has drying capacity. Even if it is completely saturated, its temperature is generally higher than that of the ambient air. But the main loss comes from the vapour produced in the air. This contains a great deal of energy which could be retrieved if we could condense it (Fig. 2).

Figure 2. Comparison of the different kind of energy losses.

Some numerical values illustrate this point.

- The energy required to heat 100 kg of maize from 20 to 70°C (the highest grain temperature encountered in French dryers) is 5.6 MJ.
- The energy required to vaporise 20 kg of water (100 kg of maize dried from 35 to 15% moisture content, wet basis) is 50 MJ.

It is clear that vaporisation of water consumes about 90% of the energy for drying.

This is the basic idea that led to consideration of steam rather than air as a drying medium. Since the drying medium and the gas produced are the same, it offers some interesting possibilities:

- the steam produced, when recompressed or heated, is able to replace the condensed drying medium (closed loop)
- there is no rejection of fines (no air wastes)
- a higher drying rate is possible (mainly due to the high temperature)

However, steam drying also has a number of disadvantages:

- much higher cost (boiler, high technology dryer, etc.)

[Diagram: Energy, multi-product ability, installation investment, quality, moisture content, product flowrate, production cost and simplicity, fill in with your specific objectives]
• quality degradation due to the high temperature (reverse conclusion in certain cases).

It is important to note that drying with superheated steam implies boiling of the water in the product. The dried products thus differ from those obtained by hot air drying.

We may say that, due to its high investment cost, steam drying is reserved for very high production capacities and convection-limited products (i.e. diffusion is not the limiting factor of the drying rate).

It is important to categorise the energy optimisation possibilities:
• conception level—choice of the drying medium (air, steam, microwaves, etc.), heating device (electrical, fuel, etc.), design of the dryer;
• tuning level—settings of the dryer (temperature, flow rates, etc.)
• control level—control algorithm (setpoints, desired performance)

The first level (conception) differs from the others in that the dryer does not exist yet at this point. The choices must be made by considering the environment constraints: what is the cheapest energy available? Do we have the technological environment to produce and use steam?

How does one tune an existing dryer for optimal running? The best answer would come from simulation tools (model-based computer aided design (CAD) software; see section on modelling) and the dryer design. In the more general case, the answer comes from previous knowledge and thus can be considered to be sub-optimal.

How does one tune an existing dryer for optimal running? The best answer would come from simulation tools (model-based computer aided design (CAD) software; see section on modelling) and the dryer design. In the more general case, the answer comes from previous knowledge and thus can be considered to be sub-optimal.

Figure 3 shows theoretical curves comparing performance using manual and automatic control. It has been widely verified that automatic control leads to a narrower distribution of the moisture content of the product at the output. Thus, the setpoint is approached more closely and the energy consumption is reduced.

Drying capacity

As previously discussed, both the drying capacity and the energy efficiency must be considered. For a continuous dryer, drying capacity is inverse proportional to the residence time (i.e. drying time) of the product. For a discontinuous dryer (e.g. a crib), it is proportional to the size of the dryer since the residence time is very long.

As an example, typical production capacities in France (for a maize mixed flow dryer operating to reduce moisture content from 35 to 15% wet basis) ranges from 30 to 100 t per hour.

Clearly, the production capacity should be defined at the design level, considering the requirements and the effective (decreasing) drying rate of the product. Best solutions are obtained with the help of a simulation tool (model-based CAD software).

If we consider a deep bed of grain, dried by hot air flowing from the bottom to the top, where the input air characteristics are 100°C and 1% relative humidity (r.h.), two contrasting cases can be considered for the output air characteristics (Fig. 4):
• either we want the best production capacity (lowest drying time)—airflow rate should be as high as possible to maintain the same drying capacity everywhere in the bed; or
• we want the best energy efficiency—airflow rate should as low as possible to use completely the drying capacity of the air (100% r.h. and 10°C at the output)

It is obvious that increasing the airflow rate will increase the global drying efficiency of the bed (including the production capacity) while considerably decreasing its energy efficiency. Conversely, a low airflow rate will ensure high energy efficiency and better quality while greatly reducing the production capacity (due to long drying time).

Figure 3. Automatic control reduces the moisture heterogeneity and thus better fits the requirements.
Quality

During the 1970s, energy efficiency was the most important factor to consider when designing and operating dryers. Today, quality is becoming increasingly important, perhaps more important than energy when drying rice in western countries.

Rice is a good example, since broken kernels cannot be used for human food markets and thus their value is only one-tenth that of whole kernels for the same production cost.

Many authors have studied phenomena associated with the degradation of the quality of rice kernels (Kunze 1979, 1996). The wet-milling quality of maize (Courtois et al. 1991), the baking characteristics of flour, and the viability of wheat seed (Nellist 1981; Nellist and Bruce 1987) have also been studied. These last studies have developed models describing the relation between quality degradation and drying variables (grain moisture and temperature).

We have shown (Courtois 1991; Courtois et al. 1994) that the wet-milling quality of maize is mainly influenced by the thermal treatment, independently of any drying phenomena. Using water baths, after one hour at fixed temperatures, the quality was considerably reduced for temperatures above 50°C (Fig. 5).

Bonazzi et al. (1994) describe an interesting comparison between two different kinds of experimental treatment:

- one hour drying of rice; and
- one hour of thermal shock without drying (see above).

Quality was measured as head rice yield (in a processing unit). Results are presented in Figure 6.

Obviously, the quality is not affected if no drying occurs even at high temperatures. This quality criterion is a physical one, as opposed to the biochemical criterion used for the wet-milling quality of maize.

Unfortunately, there are only a few products for which quality models are available. This is partly due to the high cost of the experimental work required for this purpose. Another important reason arises from the fact that quality is more a constraint than a real objective to maximise. Generally, the operator chooses a quality limit below which the dryer should not operate.

General-purpose dryers

A major component of the cost of a dryer is attributable to its limited use: about one month from the beginning of the harvest. As an example, in France, grain dryers work only 3–4 months a year for an approximate investment of US$400000. It is thus obvious that research on grain drying should focus more on the multi-purpose capabilities of industrial
dryers. Realistically, however, we must admit that there is no industrial dryer available that could dry grains, pet foods, or flours equally well.

The Modelling Approach

It is difficult to say if there might be a universal solution to all the problems listed above. In particular, we did not consider the additional constraints specific to developing countries. From our point of view, the gain in performance will be achieved more by the use of modern tools such as models and automatic controllers, than by specific technologies. An interesting illustration of this is the superheated steam widely used for liquid concentration (evaporators) but very poorly used for the drying of solids in western countries. This is mainly because of the very high cost of these technologies. These remarks can also be applied to several other technologies, such as freeze-drying and vacuum-drying.

Models are useful for a number of reasons. First, there are many good drying models in the literature for most cereals (Toyoda 1988; Bakker-Arkema et al. 1974). Moreover, it is not expensive to adapt existing models to other products. Second, models allow the testing of the best design of a dryer reducing the development cost and optimising the performance obtained. This is particularly useful since the drying time varies widely with the air characteristics (Fig. 7).

Third, combining drying and quality models enables the global optimisation of the design and settings of the dryer. It provides online assistance to the operator to determine the best settings for the desired performance (Fig. 8).

For practical reasons (mainly the destructive methods used for quality measurements), the confidence intervals on quality predictions are much larger than those for drying. As shown in Figure 9, the validation of the quality model gives a poorer agreement between experiments and simulations compared with those observed for the drying model.

The Control Approach

It would be difficult to list all the possibilities that would flow from the availability of a good model combining drying and quality (Trystram and Courtois...
We will emphasise here the use of a model in a model-based predictive control algorithm used to control a fixed-bed maize dryer.

A study in progress (Trelea et al. 1995a) concerns the optimisation of batch drying. The study focuses on the fixed-bed drying of a thin layer of maize. The wet-milling quality of the maize is considered as well as its moisture content (Fig. 10).

Two recurrent neural networks have been identified to speed up the online prediction of moisture content and wet-milling quality of maize (Trelea et al. 1995b). These models are coupled with optimisation techniques to determine the best air temperature to achieve the correct final moisture content at the desired drying time, and to ensure that the quality stays within required boundaries. Uncertainties in the state variables are taken into account.

Figure 11 plots the results of an experiment conducted to observe the efficiency of the controller during a simulated disturbance (heating resistors were decoupled for one hour). Despite this, the algorithm has succeeded: final moisture content is under the desired value and the quality is maintained above its limit.

The interest in this method lies in its generalisation ability. The lack of assumptions concerning the model, the general formulation, and the very good performance are important advantages to consider.

**Conclusion**

Grain drying remains open as a domain for researchers. There is a multitude of publications to support this assertion (e.g. proceedings of drying symposiums). However, these studies may diverge from developing countries' considerations and needs. They generally do not take into account either practical constraints encountered in developing countries or the multi-purpose ability required.

**Acknowledgments**

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CONTRIBUTED PAPERS
Grain Drying as a Means of Reducing Harvest Losses

Yahya Abawi*

WHEAT and sorghum are major winter and summer crops grown in north-eastern Australia. Bad weather during harvest can cause considerable delays to harvesting, resulting in substantial yield and quality losses. On average some 10% of Australian wheat is downgraded to feed quality because of summer rains. Harvesting of sorghum is normally carried out in late autumn and early winter. Overnight dew, high relative humidity, and shorter day length prevent rapid drying of the grain in the field. Clearly, high moisture harvesting and drying of the grain can reduce weather-related damage and yield losses. A simulation model of grain harvesting and drying was developed to examine the economics of high moisture harvesting and drying. The results show that the optimum harvest moisture content for wheat is between 14 and 18% (wet basis) and for sorghum is around 18% (wet basis). This paper outlines some strategies for minimising grain losses caused by adverse weather during harvest.

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Minimum Daily Temperature as a Predictor of Dewpoint Temperature

Yahya Abawi*

PSYCHROMETRIC data, such as relative humidity, dewpoint temperature, wet-bulb temperature, and vapour pressure, are used in the simulation of many grain drying and aeration systems. However, availability of such data is limited to a few meteorological stations, and records are often short and incomplete. On the other hand, long-term records of daily minimum and maximum temperatures, from which hourly values of dry-bulb temperature can be generated using published models, are widely available. In this paper, regression analysis is used to relate dewpoint temperature to daily minimum temperature. Once the dewpoint temperature is known, all remaining properties of air can be computed from the dry-bulb temperature and the psychrometric equations.

Materials and Methods

Seven meteorological stations in Queensland and New South Wales were selected to represent contrasting climatic conditions for this study (Fig. 1). The minimum data set used in the analysis included daily minimum and maximum temperatures, rainfall, and dry- and wet-bulb temperatures at 0900h and 1500h. For each location, a minimum of 15 years of data was available for regression analysis. At each location, daily dewpoint temperatures were calculated at 0900h and 1500h. If the difference in dewpoint temperatures between the 0900h and 1500h was greater than 6°C, the data were discarded and assumed to have measurement errors (this accounted for about 4% of all available data). Daily variations of more than 6°C in dewpoint temperature are extremely rare and could occur only with sudden change in atmospheric conditions such as a storm.

To establish a relationship between the dewpoint temperature and the minimum daily temperature, the average daily dewpoint temperature (mean of 0900h and 1500h) was correlated with daily minimum temperature, for each location. Regression coefficients were derived for each month, to determine the seasonal variability of the correlation. Separate regression coefficients were derived for dry and wet days so that the effect of wet days on the relationship between the dewpoint and minimum temperature could be found.

Results and Discussion

Correlation between daily minimum temperature and average dewpoint temperature

Significant correlations were found between the daily minimum temperature and the average dewpoint temperature. More details of the results and the monthly regression coefficients for each location are given in Abawi (1994). The correlation was generally higher ($R^2 = 0.70, P < 0.01$) during the southern winter, when the differences between the daily minimum temperature and the dewpoint temperature are smaller. The correlation was lower ($R^2 = 0.3, P < 0.01$) during the southern summer, particularly for the drier regions (Charleville and Roma) where the differences between dewpoint temperature and minimum air temperature are larger. During summer, the correlations were generally lower for wet days than for dry days, partly because of the subjective definition of what constitutes a wet day, as discussed later.

For each location, daily value of dewpoint temperature was calculated from 1957 through to 1973. The calculations were based on the daily minimum temperature, state of the day (dry or wet), and the regression coefficients. The average daily dewpoint depressions (minimum temperature minus dewpoint temperature) for Charleville, Emerald and Dalby (as representative locations) for dry and wet days are shown in Figures 2 and 3.
Figure 1. Locations used in the study.

Figure 2. Seasonal and locational variability in dewpoint depression. Data points are average daily depression (1957–1973) for days without rain.

The results show that dewpoint depressions are spatially and seasonally dependent. Dewpoint depressions increase with the distance from the coast and show a distinct seasonal trough with the minimum occurring during the cool winter months.

For fine days, the average daily depression during summer ranged from 2°C for Dalby (200 km inland) to 10°C for Charleville (1000 km inland) (Fig. 2). During winter, the dewpoint depression was about 1°C for all locations more than 200 km inland. For Dalby, the dewpoint depression was negative during winter, indicating that dewpoint occurs before minimum daily temperature is reached.
For wet days, the dewpoint depression was close to 1°C for most locations, particularly during winter (Fig. 3). The results for wet days showed considerable scatter, especially during summer at inland locations such as Charleville. This is largely because wet days were defined as days with more than zero mm of rain and, consequently, many days with less than 1 mm of rain were classified as wet days. Dewpoint temperatures are up to 10°C below the daily minimum temperature on dry days and only 2–3°C below on wet days.

In the absence of direct data on dewpoint temperature, researchers have often assumed that the dewpoint temperature occurs at minimum daily temperature and, based on this assumption, have predicted agroclimatic data such as relative humidity, wet-bulb temperature and vapour deficit (Carberry and Bristow 1991). The results from this study show that the general assumption of minimum daily temperature as a substitute for the dewpoint temperature is not valid and could lead to significant errors, particularly for arid regions where the difference between the daily minimum temperature and the dewpoint temperature could be up to 10°C.

Besides seasonal and spatial effects, other variables such as altitude and the daily temperature range may influence the relationship between the daily minimum temperature and the dewpoint temperature. This is currently being examined.

**Correlation between 0900h and 1500h dewpoint temperature**

Calculation of hourly psychrometric values from the dewpoint temperature is usually based on the assumption that the dewpoint temperature remains relatively constant throughout the day (Kimball and Bellamy 1986; Campbell 1977; Bristow and Carberry 1991). This assumption was tested by plotting the calculated dewpoint temperatures at 0900h against the dewpoint temperatures at 1500h. The data for one year for Goondiwindi are presented in Figure 4 as a representative sample which shows that dewpoint temperatures were generally higher at 0900h than at 1500h, particularly on fine days. During wet days the dewpoint temperatures were nearly the same at 0900h and 1500h. These results suggest that in certain applications, such as in the simulation of grain aeration and drying systems, where hourly values of air properties are needed, the relationship between the 0900h and 1500h dewpoint temperature needs to be taken into consideration.

**Prediction of hourly psychrometric data from daily temperatures**

To assess the reliability of the method for predicting hourly data, 29 years (1957–1985) of daily minimum and maximum temperatures and rainfall for Goondiwindi and Dalby were used to generate hourly dry-bulb temperatures using the algorithm proposed by Kimball and Bellamy (1986). The regression coefficients were then used to predict daily dewpoint temperature from minimum air temperature and daily rainfall. Dewpoint temperature during the day was assumed to remain constant. The psychrometric equations were then solved to compute hourly values of wet-bulb temperature and relative humidity. The average monthly values of these parameters at 0900h and 1500h and the published historical averages recorded by the Bureau of Meteorology (1957–1985) for Dalby are presented in Table 1. There is a close agreement between the predicted data, based on the regression coefficients, and the published historical data, particularly at 1500h.
Table 1. Comparison of historical and predicted air temperatures and relative humidity for Dalby (1957–1985). Station 041023: Latitude 27°11'S; Longitude 151°16'E.

<table>
<thead>
<tr>
<th></th>
<th>Mean temperatures (°C) and relative humidity (%) at 0900h</th>
<th>Mean temperatures (°C) and relative humidity (%) at 1500h</th>
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<tr>
<td></td>
<td>Dry-bulb</td>
<td>Wet-bulb</td>
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Notes:
Values in shaded columns are calculated from historical daily minimum and maximum temperatures and the regression coefficients.
Value in remaining columns are from: Climatic Averages Australia, Bureau of Meteorology, 1988.
The predicted dry-bulb temperatures at 0900h are 2–3°C below the published data, particularly during the winter months of May–August. This difference arises from the assumption in the Kimball and Bellamy (1986) model that minimum air temperature occurs shortly after sunrise. A slight lag between the predicted and actual time that minimum temperature occurs results in a large prediction error because of the steep gradient in the temperature rise early in the morning. Since the wet-bulb temperature and the relative humidity records are derived from dry-bulb temperature, an error in the dry-bulb temperature would also influence the values of these parameters. Another explanation for the difference between published and predicted data, particularly for relative humidity and wet-bulb temperature, may lie in the assumption that the dewpoint temperature remains constant during the day. Dewpoint temperature is 1–2°C higher at 0900h than at 1500h (Fig. 4) and because this bias is not corrected in these calculations, it could explain some of the differences between the observed and published data at 0900h.

Conclusions

The assumption that minimum daily temperature can be substituted for the dewpoint temperature is not valid. However, significant correlation exists between the daily minimum temperature and the dewpoint temperature. In eastern Australia, the regression parameters vary with the season, location, and the state of the day (wet or dry). The dewpoint depression (minimum temperature minus dewpoint temperature) ranged from about −1°C for coastal areas during the southern winter (May–August) to 10°C for inland locations during the southern summer (November–January). On wet days, at all locations and times of the year, the dewpoint depression was close to zero. These results can be used to predict a wide range of agroclimatic data from daily minimum and maximum temperatures and rainfall records.

References


Design and Development of a Rotary Semi-fluidised System Dryer for Paddy

T.F. Anchiboy and R.E. Manalabe*

The advent of flash dryers has been brought about by the two-stage drying technology, a proven way of minimising grain quality deterioration after harvest. The first stage of drying entails the rapid removal of surface moisture that will otherwise cause rapid quality deterioration. The successful development of mechanical dryers involves both technical and socioeconomic considerations. The latter have often been overlooked in the past, thus resulting in technologies that failed. Most Filipino farmers cannot afford a mechanical dryer no matter how simple and inexpensive the unit might be, but they are willing to pay for farm services such as threshing and harvesting. They might also be willing to pay for custom drying if an appropriate service and equipment were available. This study examines the factors considered in the design and development of a rotary semi-fluidised system dryer, or RSSD, for first-stage drying of paddy.

**Methodology**

**Ex-ante socioeconomic survey**

To analyse the various social and economic parameters that served as bases for the development of the RSSD, an ex-ante socioeconomic survey was conducted with farmers as respondents. Drying systems applicable to their operations were identified and quantified in terms of gross income, for the computation of an affordable drying fee and investment cost for the developed technology.

**Experimental model of the RSSD**

In parallel with the survey, an experimental model of the RSSD was built for laboratory testing (Fig. 1). The optimum exhaust door opening, which affects the moisture extracting capability of the drying system, was established in the test. The effect of initial moisture content of the paddy to be dried, the inflow rate, the drying air temperature, and the airflow rate on the performance of the dryer were also investigated. Paddy at 1 t/hour flowrate was dried using a temperature of 150–170°C and an airflow rate of 57 m³/minute. In another experiment, airflow was reduced to 37 m³/minute in order to investigate the possibility of reducing blower capacity and thereby its cost.

**Prototype model of the RSSD**

The prototype model of the RSSD was designed and developed based on the results of the drying experiments using the experimental model and the findings of the ex-ante study on the preferred investment cost, drying cost, and drying strategy. The prototype was performance tested. Important parameters such as the moisture extracting capability and input and output flowrates were established in the tests. A bill of materials was determined in order to evaluate the investment cost of the dryer, particularly whether it remained within the affordable investment cost limitation established in the first part of the study. Fuel consumption and labour requirements of the dryer were also recorded.

**Results and Discussion**

Seven existing and proposed drying systems were identified in the ex-ante survey as shown in Figure 2. The gross incomes from the different systems were computed, without deducting the drying fee. The results are shown in Figure 3. SVI has the advantage over the rest, followed by SIII and SVII. However, SIII is difficult to achieve during the wet season, hence SVI and SVII were compared for the calculation of affordable drying fee. The difference in gross income between the two systems was computed and divided by the volume available for drying to arrive at the affordable drying fee of approximately PHP10.00 per cavan (during October 1995, ca 25 Philippines pesos (PHP) = US$1; 1 cavan = 50 kg). Cost data of a 1 t/hour mechanical thresher were used as a starting point in determining the cost for the RSSD. Investment cost was computed by dividing the net income by the assumed payback period, and was found to be approximately PHP46,000.00.

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Figure 1. Schematic drawing of the experimental model of the RSSD. Parts of the model are as follows: 1, loading hopper; 2, screw auger; 3, perforated cylinder drum; 4, air duct; 5, blower; 6, kerosene pot type burner; 7, gasoline engine; 8, electric motor and; 9, unloading port.

Figure 2. The seven identified drying systems.

Figure 3. Gross income for the seven identified drying systems.
An experimental model of the RSSD was fabricated and used for preliminary testing. Table 1 summarises the results of the first laboratory test. At a residence time of 20 seconds, the resulting moisture extraction averages 3.8% resulting in an input capacity of only 0.58 t/hour, well below the target capacity of 1 t/hour.

Table 1. Performance testing of RSSD experimental model at varying exhaust door opening.

<table>
<thead>
<tr>
<th>Exhaust door opening</th>
<th>1/4</th>
<th>1/2</th>
<th>3/4</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum ang. vel., mps</td>
<td>1.61</td>
<td>1.61</td>
<td>1.61</td>
<td>1.61</td>
</tr>
<tr>
<td>Blower speed, rpm</td>
<td>2705</td>
<td>2695</td>
<td>2712</td>
<td>2705</td>
</tr>
<tr>
<td>Drying air temp, °C</td>
<td>100</td>
<td>100</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Grain temp, uncooled, °C</td>
<td>*</td>
<td>50</td>
<td>*</td>
<td>56.5</td>
</tr>
<tr>
<td>Cooling duration hr</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Grain temp, °C (cooled)</td>
<td>*</td>
<td>33.5</td>
<td>*</td>
<td>32.5</td>
</tr>
<tr>
<td>Airflow, m³/min</td>
<td>56.68</td>
<td>56.68</td>
<td>56.68</td>
<td>56.68</td>
</tr>
<tr>
<td>Res. time, sec.</td>
<td>18.70</td>
<td>19.61</td>
<td>20.86</td>
<td>21.19</td>
</tr>
<tr>
<td>Initial m.c., % w.b.</td>
<td>22.07</td>
<td>21.88</td>
<td>24.23</td>
<td>25.35</td>
</tr>
<tr>
<td>Final m.c., % w.b.</td>
<td>18.40</td>
<td>18.52</td>
<td>20.18</td>
<td>21.29</td>
</tr>
<tr>
<td>Moist. reduction</td>
<td>3.67</td>
<td>3.36</td>
<td>4.05</td>
<td>4.06</td>
</tr>
<tr>
<td>Total drying time, sec</td>
<td>110.8</td>
<td>118.0</td>
<td>133.3</td>
<td>138.5</td>
</tr>
<tr>
<td>Capacity, t/hour</td>
<td>0.65</td>
<td>0.61</td>
<td>0.54</td>
<td>0.52</td>
</tr>
</tbody>
</table>

With the loading hopper regulator fully open, the highest grain input flowrate of 0.83 t/hour was achieved. Decreasing the drum speed from 78 to 60 rpm decreased the residence time to only 7 seconds, thus increasing the grain output flowrate (Fig. 4). With the decrease in the grain residence time, the moisture extracting capability of the dryer also falls (Fig. 5). Figure 6 shows that as drum speed decreases, grain flowrate increases to a peak at 50 rpm, then gradually falls again as drum speed continues to decrease. It was also observed during the drying experiments that the highest possible drying air temperature, without resulting in a kerosene odour in the exhaust, ranged from 150–170°C. Quality analysis done in terms of brown rice, milled rice, and headrice recovery showed no significant differences between samples taken before and after drying.

The combined effect of high drying-air temperature and low airflow at 1 t/hour flowrate in the preceding experiment was not very encouraging in terms of moisture extraction (2.1% per pass). For this reason, another experiment was conducted, using 57 m³/minute airflow instead of 37 m³/minute. The results are summarised in Table 2. At 150–160°C drying air temperature and approximately 57 m³/minute airflow, the resulting moisture extraction was 3.9%. The initial moisture content of the sample used was relatively low at 22.0% (wet basis), and the actual output capacity was calculated to be 0.90 t/hour. Results of the quality analyses done on samples before and after drying paddy with high drying-air temperature and high airflow showed no significant difference in brown rice and milled rice recovery but for the headrice recovery, the initial sample (before drying) had a relatively lower headrice yield than samples after drying (Table 3). This could be attributed to the gelatinisation effect of using high drying-air temperature and high airflow during the flash-drying operation.

![Figure 4. Exposure time of paddy at different drum rotation speeds of the RSSD.](image)

![Figure 5. Moisture reduction of paddy at different initial moisture contents and residence times.](image)
Figure 6. Grain flowrate at varying drum rotation speed.

Table 2. The effect of flash drying paddy with 150–160°C drying air temperature and 57 m³/minute airflow on moisture extraction of paddy.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Initial m.c. (% w.b.)</th>
<th>Ambient temp. (°C)</th>
<th>Grain temp. (°C)</th>
<th>Final m.c. (% w.b.)</th>
<th>Moisture reduction (%)</th>
<th>Grain flowrate (t/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>22.0</td>
<td>32.5</td>
<td>55.0</td>
<td>18.1</td>
<td>3.9</td>
<td>0.894</td>
</tr>
<tr>
<td>II</td>
<td>22.4</td>
<td>32.2</td>
<td>55.0</td>
<td>18.3</td>
<td>4.1</td>
<td>0.888</td>
</tr>
<tr>
<td>III</td>
<td>22.5</td>
<td>33.6</td>
<td>55.0</td>
<td>18.8</td>
<td>3.7</td>
<td>0.923</td>
</tr>
</tbody>
</table>

Table 3. Summary of the quality analysis of flash dried paddy using 150–160°C drying air temperature and m³/minute airflow.

<table>
<thead>
<tr>
<th></th>
<th>% Brown rice</th>
<th>% Milled rice</th>
<th>% Head rice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial sample</td>
<td>76.3</td>
<td>64.4</td>
<td>83.9</td>
</tr>
<tr>
<td>Trial I</td>
<td>75.8</td>
<td>64.4</td>
<td>88.0</td>
</tr>
<tr>
<td>Trial II</td>
<td>76.5</td>
<td>64.6</td>
<td>88.0</td>
</tr>
<tr>
<td>Trial III</td>
<td>76.7</td>
<td>64.8</td>
<td>88.4</td>
</tr>
</tbody>
</table>

The prototype model of the RSSD (Fig. 7) was designed and fabricated based on the results of the various drying experiments. The loading hopper of the developed dryer is provided with a regulator to control the input flowrate of the grain. Likewise, a separate auger pulley is provided to make the auger speed independent to the speed of the rotating drum. Thus, the optimal drum speed could be set to achieve fluidised-drying of grain at 1 t/hour input flowrate (as can be regulated separately through the auger speed).

A plenum air manifold is provided with air diverters to achieve equal distribution of drying air to the entire length of the rotating drum. Exhaust air is vented through a duct with a 10 x 20 cm opening at the side opposite the plenum air duct. An axial fan was used in the dryer rather than a centrifugal blower because the resulting static pressure of the dryer is less than 1 inch of water gauge. Also, axial fans are cheaper than centrifugal blowers. The computed bill of materials for the RSSD prototype was PHP42,927.50.

Results of the performance testing of the prototype model showed that the average moisture reduction of paddy is 4.1% per pass, at a residence time of 40 seconds. The average kerosene consumption was 5.6 L/hour and the average gasoline consumption of the engine used for the blower 1.5 L/hour. Input capacity was maintained at 1 t/hour, with a drying air temperature of 160°C, and an airflow of 57 m³/minute. The labour requirement for the entire drying operation was at least 3 persons.

Conclusions and Recommendations

1. The RSSD was designed and envisioned to give the highest return in the wet season, especially during days of continuous rain when one day of sun drying is not sufficient to completely dry the paddy to a safe moisture level.

2. The mechanical drying fee affordable to farmers was estimated to be approximately PHP10.00 per cavan of paddy.

3. The investment cost affordable to farmers for the RSSD is estimated at PHP46,000.00.

4. As drum speed decreases from 80 revolutions per minute, grain flowrate increases up to its peak at 50 rpm, then decreases again as drum speed continues to decrease down to 35 rpm. A 1 t/hour input capacity can be obtained with 50 rpm drum speed and 14.2 % moisture content of the paddy.

5. The optimum drying air temperature for the RSSD was in the range 50–170°C. With this drying air temperature and a 37 m³/minute airflow, the resulting moisture extraction was only 2.1%. When an airflow of 57 m³/minute was used, the resulting moisture extraction increased to 3.9 %, without significantly affecting grain quality.

6. Based on the conclusions drawn from the drying experiments conducted, the prototype model of the farm flash dryer must be operated with a fully open loading hopper. The drying air temperature to be used for flash drying paddy at 1 t/hour flowrate must not exceed 150–170°C.
7. The total material cost of the dryer developed was PHP42,927.50. The drying cost can be ascertained only after pilot testing of the technology. This has yet to be done.

8. Further studies should also be done to investigate the possible use of the dryer in drying crops other than paddy, such as maize and other cereal grains, soybean, and mungbean.
Chilled Aeration/Storage of Grain in Southeast Asia

F.W. Bakker-Arkema*, D.E. Maier†, and A. Sebastianelli§

Abstract

The storage of grains under tropical conditions requires close supervision. This is true even for grains dried properly and uniformly to 13–14% moisture content. A major problem is the resistance of the major grain pests to the few chemicals still permitted for use. Grain chilling may be a solution to this problem.

Thailand and Malaysia are among the countries in the Southeast Asian region in which grain chillers are operating successfully. Indonesia, the Philippines, and Vietnam are researching the new technology and are expected to adopt on a limited scale the chilled aeration/storage of grains in the near future.

Experience with commercial grain chillers in the tropics has thus far shown the following:

• A chilling unit can maintain a constant temperature and relative humidity of the air entering a grain bin regardless of the ambient conditions.
• The cool-down of a bin of grain is a rapid process, and thus a chiller can be used for a series of bins.
• The re-chilling of grain by chilled aeration is required relatively infrequently due to the favourable thermal properties of the grain.
• The electrical energy use of long-term chilled-grain storage is low.

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Promoting Grain Storage Technology and Best Practice through Short Courses

R.J. Banyer* and J.H. Kent†

For businesses to remain competitive and sustain profitability, staff must possess the competencies required to carry out best practice. One significant impediment to staff development is the lack of suitable or accessible training of high quality. Educational institutions have an important role to play in the provision of such training.

Over the past six years, Charles Sturt University, a nationally and internationally recognised provider of distance education, has successfully conducted an industry short course dealing with all aspects of preservation of grain quality in storage. Emphasis is given to promoting the latest technology in the protection of stored grain. The course, based on self-paced learning on-the-job, attracts supervisors and operators of grain storages throughout Australia. Industry leaders service a follow-up skills training workshop and field excursion. Modified for Asian conditions, the course could service specific training needs of internationals.

Course Structure and Mode of Delivery

The course has two main parts:
- a knowledge component presented in a manual form designed for self-paced learning at home; and
- a practical component presented by visiting experts, either in Australia or off-shore.

Course Requirements

- Total time required to complete course requirements will vary according to an individual's program.
- Assessment of learning outcomes is based on open-book questions submitted as assignments.
- Assessment of the practical component is conducted immediately following each discrete session.
- The cost for course tuition will vary according to an individual's training program and location of the practical component.
- Sources of financial assistance are currently under review.

Award

- A Charles Sturt University Certificate of Achievement detailing competencies gained is issued on completion.

Main Features of the Course

- Quality learning materials are presented in a user-friendly format.
- Modules are designed for self-paced study at home.
- The course is structured and delivered to suit individual specific training needs.
- Expert instruction and personal tuition are provided for practicals.
- Learning materials are supplemented with up-to-date technical references including visual aids.
- A University Certificate of Achievement is awarded.
- The main topics of study are presented as discrete but interrelated modules.

Course Content

Participants may select a program of training from the following main areas:
- Grains industry in perspective—an overview of organisational structure, marketing and standards.
- Storage types and systems—design, maintenance, problems, and modifications.
- Grain characteristics and behaviour in storage.
• **Hygiene and sanitation**—first line of defence—principles and practices.

• **Grain pests**—vertebrates and invertebrates—problems caused, characteristics, identification and control; resistance management.

• **Grain quality monitoring and standards**—inspection and detection methods, sampling theory and practice, quality assessment and testing, identification of grain defects and contaminants; mycotoxins.

• **Controlled atmospheres, drying, aeration, and refrigeration.**

• **Fumigants and fumigation.**

• **Grain protectants**—choice; strategic use; application; safety and regulation.

• **Integrated management programs**—total quality management strategies; integrated pest management.

• **Occupational health and safety.**