Advances in research on in-store drying

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Abstract

In-store drying (near ambient air drying) has been used in temperate climates by the grain industry since about 1950. Current research has adapted this technique to the humid tropics, by means of computer simulation based on long-term climatic records, combined with application of automatic controllers.

This paper focuses on its application to crops prone to rapid quality deterioration, such as paddy and maize. Quality models are discussed for the dynamics of aflatoxin build-up in storage. Drying strategies are presented which take into account quality parameters for each crop.

The effects of modification of the traditional design (such as grain stirrers), and the interfacing of in-store drying with the post-harvest chain, are shown to be logistically and economically feasible.

Introduction

The main objective of drying of farm produce is to reduce the water activity of a product from its harvest level to a safe level for extended storage. After drying, the rate of deterioration due to respiration of the grain, and to insect, chemical, bacterial and fungal activity (all of which are functions of temperature and humidity), should be minimised, resulting in maintenance of the quality of the stored product.

Grains, which are some of the most important crops worldwide, can be dried in a variety of ways. The traditional method for centuries has been sundrying on the ground. The ground may be covered, bare, the compacted ground of a farmyard, or in more recent times a sealed road or the concrete clad surface of a basketball ground. The increase of grain production due to agronomic research and the mechanisation of agriculture has led to development of various techniques of mechanical drying. One major factor leading towards adoption of mechanical drying has been the increased use of large capacity bulk–handling equipment for grain. The systems which are currently in use range from high-temperature, high-capacity, single-stage, continuous-flow dryers with high energy inputs to various types of in-bulk drying systems, operating at high or low temperature, with lower energy inputs but longer drying times. There are several types of in-bulk dryers (McLean 1980) such as:

- warehouses with in-floor or above-floor aeration ducts
- ventilated silos with perforated floors and vertical air-flow (round or square)
- ventilated silos with separate inlet and exhaust ducts
- ventilated silos with vertical ducts and radial air-flow.

In addition to single-stage systems, combination or two-stage systems have been devised in order to take into account the different drying rates of grain at different moisture contents. Typically this involves high-temperature, high-speed drying in order to reduce the moisture content from its harvest level to give a product water activity of around 0.85. For rice and maize, this corresponds to a moisture content of about 18% (wet basis). This moisture, being concentrated near the surface of the grain, can be removed more easily. After completion of the first stage of drying, grain is transferred into a storage bin, where it is cooled and dried using lower air temperatures. The second stage involves removal of moisture from the centre, and so is diffusion controlled leading to a reduced drying rate. This drying stage is called the 'falling rate period'.

In-store drying is synonymous to low-temperature in-bin drying. It may be used where grain remains in store until milled or exported, or where drying is seen as the primary purpose of the equipment, with the grain being removed to another bin for aerated storage. The advantage of the latter is increase in throughput and reduction of capital cost per unit dried. This situation may arise at trader level where fast turnover of grain is required so that fresh stocks may be purchased.

The main advantages of two-stage drying are (Morey et al. 1981):

- reduced energy requirements;
- increased drying system capacity; and
- improved grain quality.

The reduced energy requirement over conventional drying technology is due to the increased air efficiency compared with continuous-flow dryers, so that less heat is vented to the atmosphere. The second point is related to the capacity of the first stage 'fast' dryer, since discharge of the grain at a higher moisture content before cooling will free the dryer for the next load of high moisture grain, which is where continuous dryers are more efficient. The third point relates to the relaxation time given the grain during second-stage drying, which allows moisture gradients within the grain to relax, preventing the outer layer of the grain from being overdried and hence made brittle and susceptible to cracking.

Conventional Systems

In-store drying has been practised in the USA since the 1950s among maize farmers in the North Central Region and rice farmers in Texas (Do Sup Chung et al. 1986). However, the technique was used mainly on a trial-and-error basis and occasionally led to spoilage of grain due to extremely low airflow rates combined with too-high drying temperatures.

Systematic studies on in-store drying began in the early 1970s when Thompson (1972) developed a mathematical model predicting changes in grain temperature, moisture content and dry matter deterioration, taking into account factors such as heat transfer through the walls of the bin, respiration of the grain mass, and conditioning of the grain through

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continuous aeration. This model was called the 'near equilibrium model'. The method of analysis was to construct a heat and mass balance across a single thin layer of material. A deep bed of grain was considered as multiple layers of grain, with a stream of air perpendicular to each layer. The initial work was for maize, the primary commercial target in the USA at the time. Farmers were required to reduce the maize moisture quickly to a level of 15.5%. Maize at too high or too low a moisture attracted a penalty. In addition, maize at too high a moisture content ran the risk of deterioration due to moulds or insects. Computer simulations were run based on this model, using weather data (temperature and relative humidity) covering long periods of time from different locations of the USA, in order to study the drying process in each place.

The technique was soon extended to other crops. In temperate climates, particularly in the USA (Barrett et al. 1981, on wheat) the U.K. (Smith and Bailey 1983, on barley) and Canada (Muir et al. 1991, on rapeseed), significant research was done on in-store drying of wheat and barley respectively. Airflow rates and weather records were studied in order to study and design in-store dryers.

Recent Research on In-Store Drying in the Tropics

Although weather conditions in humid tropical climates are less favourable than temperate climates for in-store drying, due to high ambient temperatures and relative humidities, research on the use of aeration in combination drying had began as early as the sixties (Calderwood 1966). Initially, aeration was used for cooling paddy previously dried in a high temperature dryer, by aerating a mass of grain with ambient air in a holding bin. In the late 1970s researchers in a number of subtropical and tropical countries started studying conditions for successful adoption of in-store drying of paddy, later also researching its application to crops such as maize, peanuts and soybeans. They extended the techniques initially used in temperate climates, namely optimisation by application of drying models, to tropical conditions. In order to compensate for the higher daily relative humidities, higher airflow rates and additional heat were included in the study (Adamczak et al. 1986; Driscoll and Srzednicki 1991; and Driscoll et al. 1989).

Considerable research into in-store drying of paddy was conducted in Australia from the 1970s onwards. The reason for this research was a dramatic increase in rice production in the recently created Murrumbidgee Irrigation Area in south-western New South Wales. High quality standards and the need for very competitive pricing forced the rice processors to look for the most cost-effective method for drying and storing freshly harvested paddy (Bramall 1986). The collaboration between researchers from the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and later from the University of New South Wales, who studied the fundamentals of deep-bed drying of granular solids, resulted in the development of improved strategies for in-store drying in Australia. The following conditions were determined as essential for successful drying (Bramall 1986):

- segregation of procured paddy according to moisture contents
- monitoring of grain moisture and temperature on a regular basis
- use of low speed fans
- use of aeration strategies taking into account daily fluctuations in weather conditions.

Originally, small-scale 100 t capacity radially aerated bins were used. They have gradually been replaced by bins aerated from the bottom through on-floor or in-floor ductings. The sheds currently used in the Murrumbidgee Irrigation Area have a capacity of 3000-5000 t when fully loaded, i.e. when the grain bed is 7-12 m in height. New storage bins have been installed for 'fast' drying where the grain bed is limited to 2-3 m (Semple 1988).

A series of collaborative research projects supported by the Australian Centre for International Agricultural Research (ACIAR) was launched in the early 1980s on in-store drying in the humid tropics. These projects involved Australian and international research organisations; the University of New South Wales, the Philippine National Postharvest Institute for Research and Extension (NAPHIRE), the Thai King Mongkut's Institute of Technology Thonburi (KMITT) and the Malaysian Agricultural Research and Development Institute (MARDI).

The main objectives of the research were:

- to determine thermophysical data for the main grain crops, with the aim of using these data to design drying systems for these crops;
- to investigate first-stage drying options for areas where a two-stage drying strategy was required;
- to provide appropriate technology for complete drying systems for main crops, especially paddy and maize, in the humid tropics; and
- to study the effects of various drying strategies on quality of the crop.

The results of this research have been presented at seminars and published in the literature. The following are the main outcomes from the projects:

- A very comprehensive set of weather data covering at least 10 years has been collected from various locations in Malaysia, Thailand, Indonesia and Australia (and to a lesser extent in the Philippines).
- Thermophysical data comprising bulk and true density, porosity, angle of repose, coefficient of static friction, specific heat, equilibrium moisture contents at various temperature and relative humidity levels, and thin-layer drying rates have been determined for a range of commercially important varieties of paddy and maize. Thermophysical data have also been collected for soybeans, peanuts and mungbeans.
- Baseline data regarding the structure of the grain industry in the collaborating countries in Southeast Asia have been collected. These include the geographic distribution of crops, cropping calendars, quantities procured daily by processors, and storage and milling capacities.
- A computer drying simulation model based on the thermophysical data has been developed Driscoll (1986). The model is based on thermodynamic equilibrium between air and grain during the drying process as described by Sutherland (1984). The simulation model includes grains such as paddy (Australian and Asian varieties), maize, peanuts, soybeans, mungbeans, barley and other products. Different strategies can be simulated for in-store drying, among them constant aeration, relative humidity control, time control and modulated burner control. The model makes provision for options such as recirculation of air, stirring of grain, dehumidification, and heat losses through walls.
- A great many simulations have been performed in order to assess the feasibility of in-store drying under the climatic conditions prevailing on selected sites in the main grain-growing regions of the collaborating countries in Southeast Asia. As a result of the analysis of the computer simulations it has been established that two-stage drying with in-store as a second stage is feasible under the conditions of the humid tropics.

- Confirmation of the computer model predictions was achieved by means of firstly pilot plant studies, using 1-5 t of paddy, conducted in Australia and in Asia, and secondly industrial scale experiments with up to 500 t, conducted at government grain complexes or privately owned rice mills in Southeast Asia. These experiments also demonstrated that paddy could be dried successfully during the wet season down to safe storage or milling level within the required period of 13–23 days, depending on the chosen strategy, the initial grain condition and the bed depth.
- Programmable controllers were added to the dryers. The most appropriate drying strategies for each location were programmed into these controllers, using parameters derived from computer simulation.

Quality Considerations

There are different quality standards for different grain crops, so that it is not possible to have a general quality model. However, some quality criteria are applicable to a wide range of grains; for example deterioration due to respiration or the action of certain microorganisms. Deterioration due to respiration is usually called dry matter loss, and can be determined by the amount of carbon dioxide produced, as described by Steele et al. (1969). The extent of fungal activity can be defined in a variety of ways; for example in terms of plate counts or by chemical analyses of constituents of metabolites. Some researchers (Seitz et al. 1979; Schwadorf and Muller 1989) have suggested using measurement of the amount of ergosterol present in the grain as an indicator of fungal growth. Ergosterol is a sterol found in the cell membranes of the fungi, as well as in the grain itself. Changes in the amount of ergosterol present after harvest are indications of mould activity on the grain.

Among the quality parameters of greatest economic importance for paddy is head rice yield, the proportion of head rice (rice which is 3/4 kernel size or larger) in the total amount of milled rice. Fissuring during postharvest handling of paddy will decrease the head rice yield. The mechanism of fissuring is associated with readsorbtion of moisture by grain that has already been dried (Kunze and Prasad 1978). Hence, the head rice yield is closely related to the drying strategy.

Although fissuring is also important to maize quality, a more significant quality parameter is the aflatoxin content. Aflatoxins are a secondary metabolite formed by spoilage fungi of the genus *Aspergillus*, particularly *A. parasiticus* and *A. flavus*. Aflatoxins belong to the group of difuranocoumarin compounds (Bhat 1991). They cause concern because of their potential carcinogenic effects on humans, and, in livestock production, because they lead to a significant decrease in growth rate and increase mortality among poultry and pigs. Aflatoxins are produced in a range of produce, but especially in maize, peanuts, copra, tree nuts and milk.

Improvement in quality of the dried product may often decide whether a particular drying technique is to be adopted or not. This can be shown in an example taken from a recently completed study involving in-store drying in a rice-producing co-operative in Thailand using increase in head rice as the primary quality parameter (see Table 1).

As far as aflatoxin control in maize is concerned, earlier work in the USA has shown that, when using low temperature drying, grain above 17% m.c., stored at temperatures between 13–41°C should not be exposed to relative humidities above 85% for more than 48 hours (Ross et al. 1979). Since the equilibrium relative humidity increases with temperature for a given moisture content, any delay in drying under tropical conditions combined with an increase in temperature can result in moisture adsorbtion and increased risk of aflatoxin

Table 1. Financial analysis of in-store drying facility at Chachoengsao agricultural cooperative (Soponronnarit et al. 1993).

Basic data		
Storage capacity	100 tonnes	
Establishment costs	148536 Baht	
Drying time	218.2 hours	
No of fans	1	
Fan power	11.7 kW	
Fan operating time	179.1 hours	
Electricity cost	1.65 Baht/kWh	
Assuming an increase in head yield by 5%: Internal rate of return		
Price increase in Baht/ tonne	One drying/annum	Two dryings/annum
50	7.3%	18.2%
100	11.6%	23.9%
150	14.4%	29.5%

Payback period			
Price increase in Baht/tonne		Interest	
	12%	15%	20%
50	i) >15	i) >15	i) >15
	ii) 5.2	ii) 6.3	ii) 10.5
100	i)12.9	i) >15	i) >15
	ii) 3.6	ii) 4.0	ii) 5.1
150	i) 7.8	i) 10.9	i)>15
	ii) 2.7	ii) 3.0	ii) 3.5

i) One drying per annum
ii) Two dryings per annum

formation. Recent work conducted in Thailand by Wongvirojtana et al. (1993) has shown that, with careful monitoring of the quality of incoming grain and the choice of an appropriate drying strategy, it is possible to control the aflatoxin build-up by using in-store drying technology, as shown in Table 2. However, it is feasible only for bin loading moisture contents below 19% and for low initial aflatoxin levels.

Improvement of Conventional Techniques

Conventional systems, which use fans and ducts to distribute air through the grain bed, use outside air that is conditioned to the required average relative humidity by preheating. The drying process can be controlled manually by a skilled operator systematically monitoring ambient air conditions and grain moisture content, provided he has a good understanding of the in-store drying process, or by means of a microprocessor-based controller. The first option (manual control) provides only limited accuracy, is labour intensive and needs a trained operator. The microprocessor-based controllers can be operated continuously, if necessary using a battery back-up, and are directly linked to temperature and relative humidity sensors. They execute commands from their program algorithms, which provide the intelligence for the dryer. New installations above a certain critical size will opt for automatic controllers. An automatic control system should include a possible choice of drying strategies; for example continuous aeration, relative humidity control, time control or modulated burner control. The relative humidity control option offers the possibility of integrating information from the drying model, as well as the measured grain temperature and so to continuously adjust the set-point during the drying process, resulting in a considerable saving in airflow, heater power and overall cost (Ryniecki and Nellist 1991a,b).

As previously mentioned, the drying model developed at the University of New South Wales includes recirculation of the exit air, an option which may improve the efficiency of a dryer, as described by Driscoll and Intong (1991). The advantage of recirculating a proportion of the exit air is basically of benefit to products with slow drying rates or using high airflow rates.

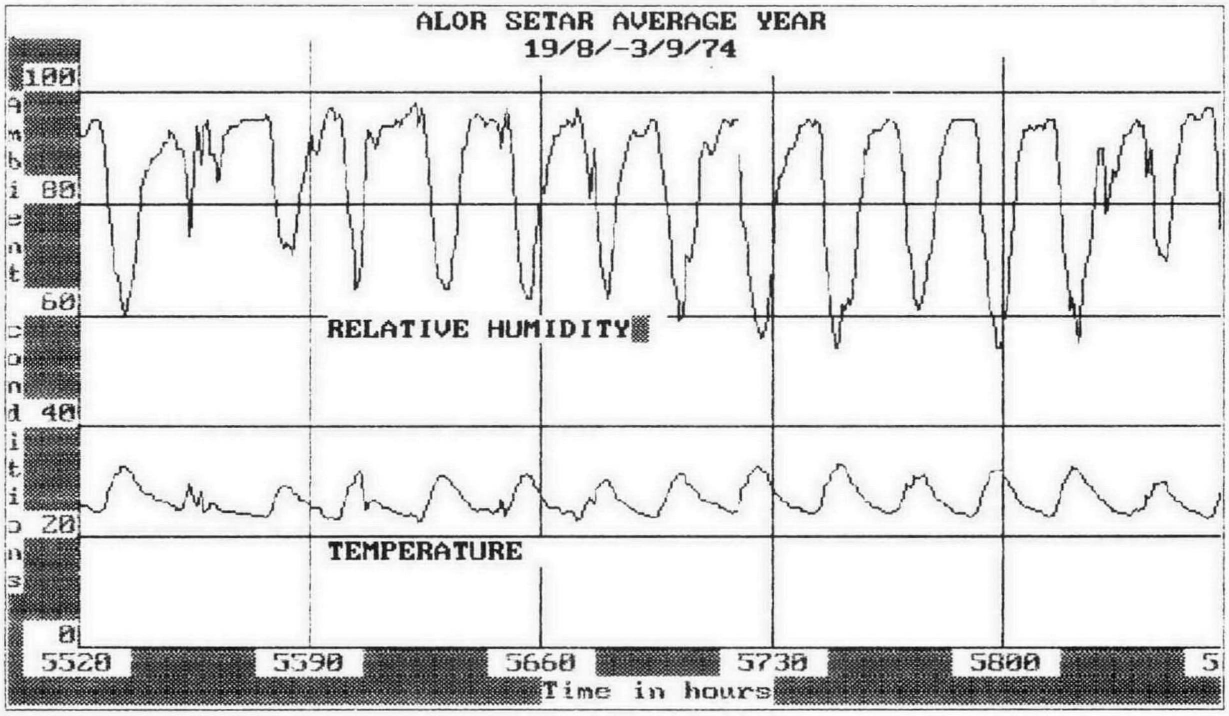
Since an in-store dryer is inherently efficient by means of the submergence of the drying front within the grain mass during most of the drying, recirculation offers little to an in-store grain drying facility until the leading edge of the drying front reaches the top of the bed, which is the last 10–20% of the drying time of a grain batch, whereafter there will be increased advantage as the exit relative humidity drops. Thus, the recirculation rate should be zero initially and then raised to 90% once the drying front broaches the top of the bed. This means the recirculation hardware (ducts and dampers) is useful only for a small percentage of the total drying time. To offset this limited advantage in energy use, recirculation will require additional capital costs, will increase pressure drop (requiring a larger, more expensive and power hungry fan), and may increase the difficulties of loading and unloading the bins. The researchers found an interesting possible advantage, which was to increase the speed of drying by increasing the amount of burner heat. If done without recirculation, the inlet grain layer would be overdried. However, by using exit air to condition the inlet air, this could be prevented while still retaining a higher air temperature. Mixing exit air with the inlet air allowed a faster drying front to be propagated through the bed. Research is continuing into whether this effect can be used to economic advantage, as the issue becomes fairly complex.

Stirring is performed with vertical augers which bring grain from the bottom layers of the stack to the surface and vice versa. It is a useful tool to prevent overdrying of the bottom layers which are the first ones to be in contact with drying air. Wilcke and Bern (1986a,b) studied the effects of stirring on dryer performance in a number of maize batches over two years. They found advantages in terms of reducing the pressure drop initially, reduction in drying time, electric energy use and prevention of overdrying. However, they found that stirring was eventually increasing airflow resistance by producing small amounts of fines and pushing them towards the plenum chamber at the bottom of the bin. Stirring is represented in the simulation by mixing the grain from all layers at set intervals.

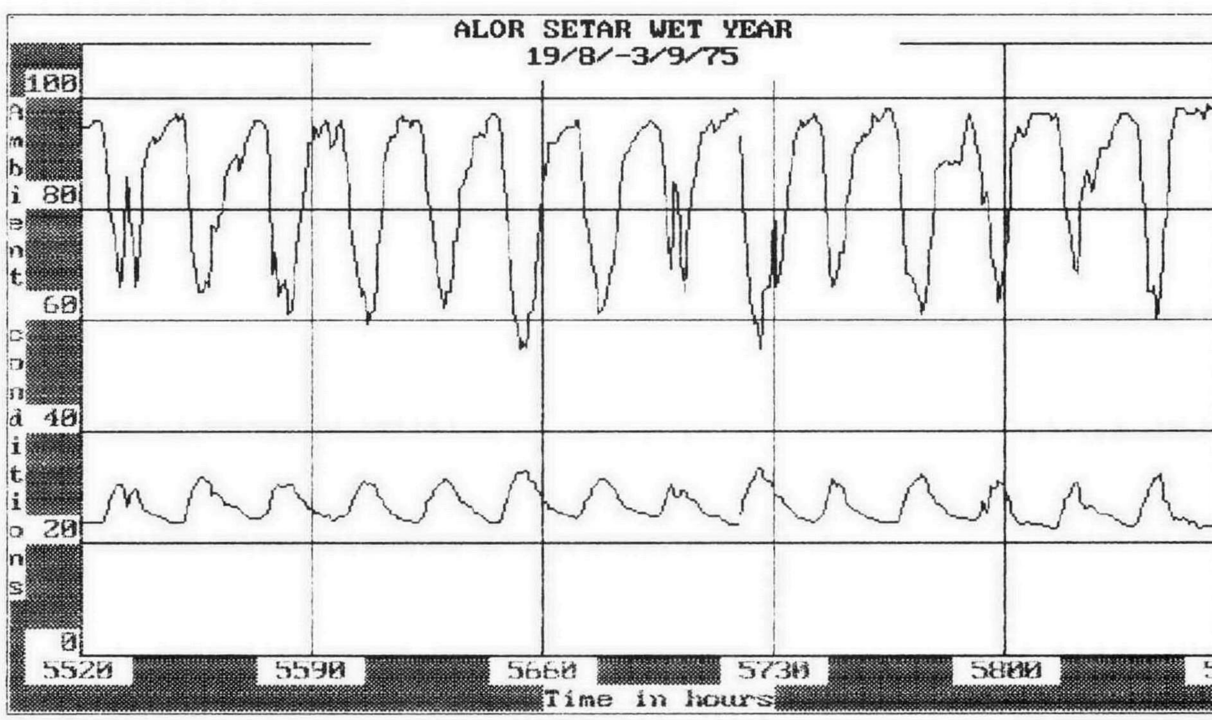
The computer simulation developed at the University of New South Wales was used by the present authors to study the effects of stirring on paddy under typical harvesting conditions for Malaysia and Thailand. The ambient conditions during that period are shown in Figures 1 and 2. The drying strategy was based on relative humidity control, with ambient air being used within 60–75% limits and additional heat being supplied from 75–95%. The maximum temperature rise (burner at full capacity) was set at 5°C and the airflow rate was

Table 2 Effects of in-store drying on final aflatoxin content under Thai conditions in a 1.4 m bed (Wongvirojtana et al. 1993).

Basic data	Experiment					
	i) Cont. aeration	ii) Cont. aeration	iii) Cont. aeration	iv) Cont. aeration	v) Time control (12 hours on)	vi) Time control (12 hours on)
Initial moisture content in % wb	19.1	25.5	20.3	20.8	17.3	18.0
Airflow rate in m^3/minutes/m^3	3.0	4.5	1.5	2.5	4.0	2.5
Ambient conditions						
Relative humidity in %						
Average	85.0	83.0	75.8	87.7	76	82.9
Range	62–98	58–98	43–98	70–98	40–98	60–93
Temperature in °C (average)						
	28.0	28.0	25.9	27.0	27.0	26.7
Drying time (hours)	144	216	360	264	132	244
Aflatoxin content in ppb						
Before drying	0	16	51	48	119	274
After drying	0	666	61	282	69	187

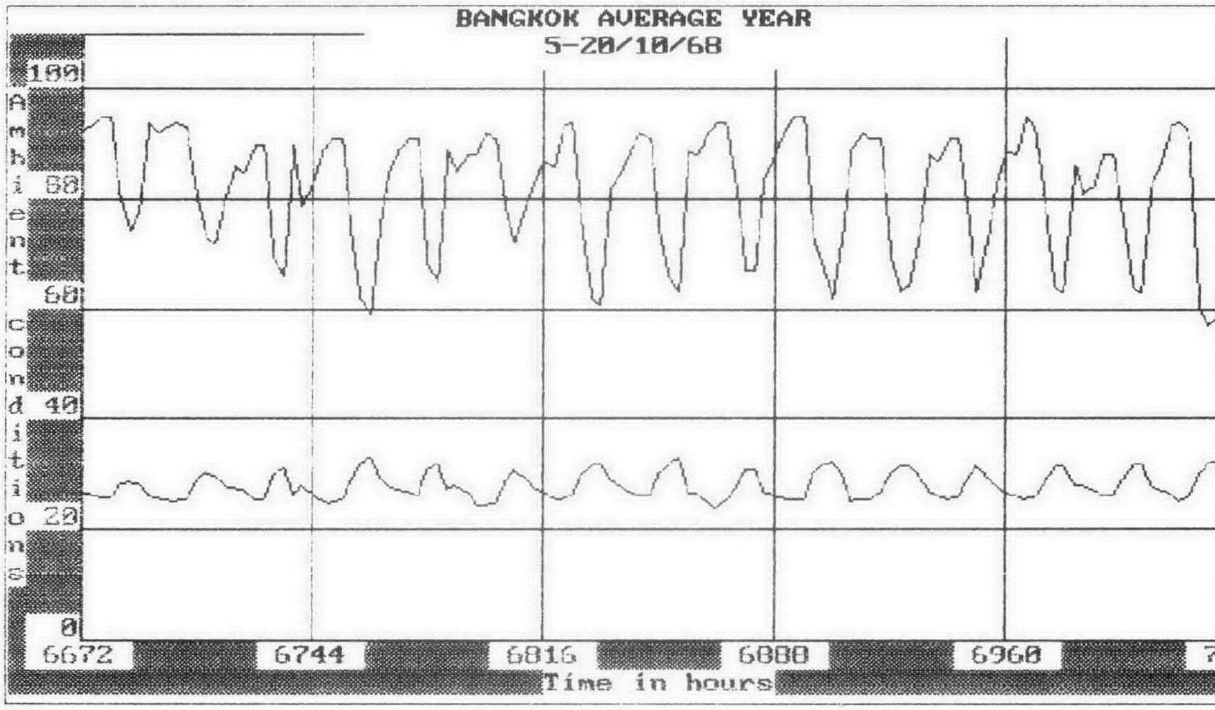


A) Average year

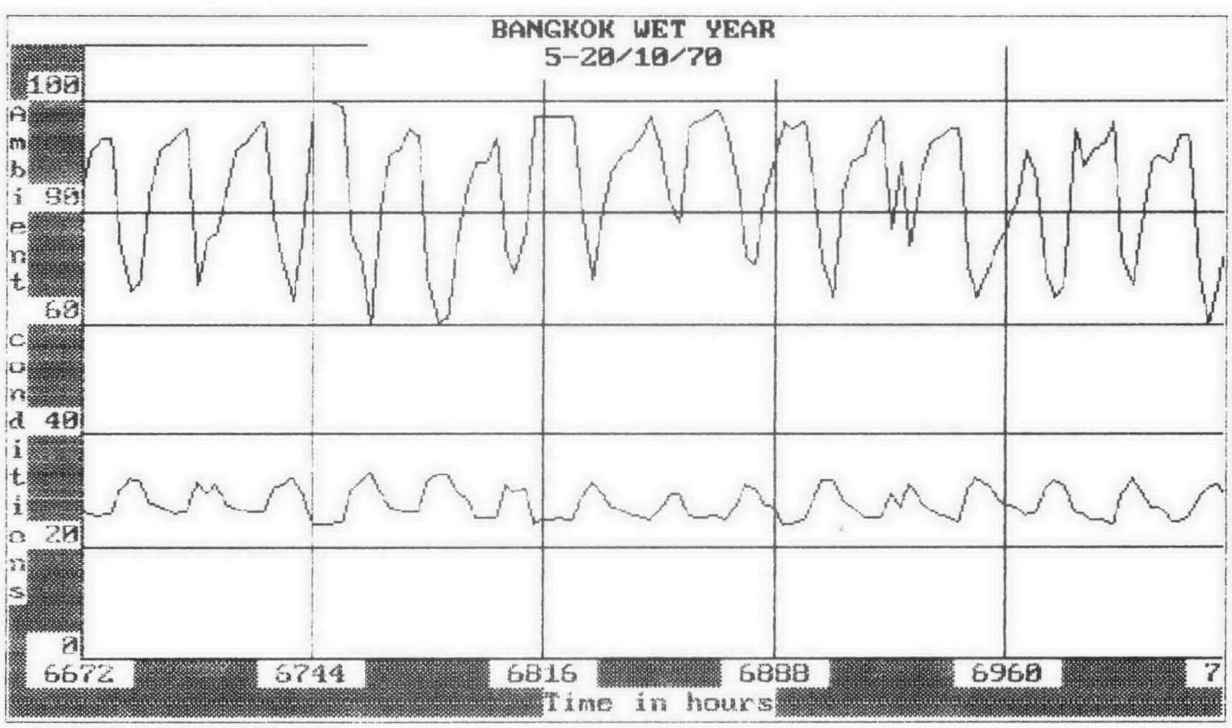


B) Wet year

Fig. 1. Weather pattern during wet season in Northeast Malaysia. A) Average year; B) Wet year.



A) Average year



B) Wet year

Fig. 2 Weather pattern during wet season in Central Thailand.

set at 8.6 mL/minute. Under these conditions, the effects on the moisture gradient within a 3 m bed are shown in Figure 3. It appears that stirring has a dramatic effect in reducing the top-to-bottom moisture differential in the grain bed. The effect is noticeable in average as well as in wet years but appears more pronounced in average years.

Conclusions

In concluding this paper, we can say that the recent research on in-store drying has explored various ways of fine-tuning the technique in order to optimise the use of ambient air for drying of grain. Computer simulations have been used to investigate possible applications in the humid tropics. The technique has proven feasible under tropical conditions, but within stricter operating limits than for temperate climates. More consideration is currently being given to the quality of the final product, but additional systematic studies are required for a fuller understanding of the mechanisms of product deterioration, especially related to the formation of mycotoxins. Improvement of conventional methods, namely through inclusion of recirculation and stirring, are proving to have a favourable effect on energy cost and product quality. Yet it is unlikely that recirculation for in-store drying will ever be economically effective. Microprocessor-based control systems are an essential tool for optimising the drying systems. Future directions in the development of in-store drying for Australian conditions may well be along the lines of model-based control, where sufficient fundamental data on the drying properties of the product have been provided in order to develop accurate process algorithms.

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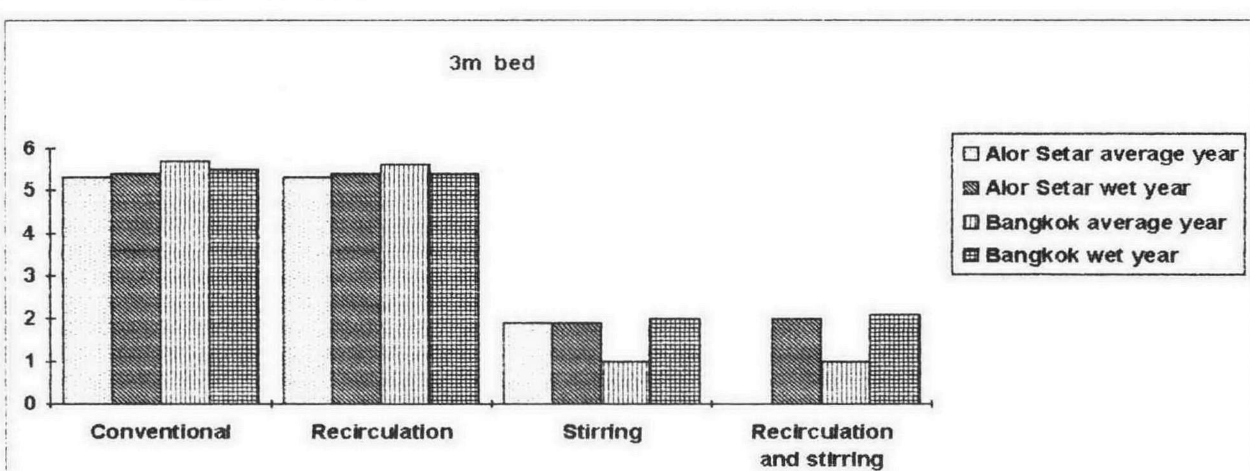

Fig. 3 Effects of recirculation and stirring on top-to-bottom moisture differential in paddy

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