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HEAT PUMP DRYER FOR FRUIT USING R22 AND R134a AS WORKING FLUID

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Keywords: agricultural product; bananas; refrigerant

ABSTRACT

The objective of this work is to study the performance of heat pump dryers using single circuit of R22 refrigerant and double circuits of R134a refrigerant. The theoretical analysis was done by varying evaporating temperatures from 0-20^{0}C and condensing temperatures from 45-60^{0}C. The theoretical results shown that the performance of heat pump in terms of heating effect and COP_h operating on R22 are 8%, and 1%, respectively, relatively higher than that operating on R134a. In the experiments, bananas is dried by using heat pump dryers. In order to control a drying temperature, the dryer of double circuits of refrigerant operates with one circuit when the drying air is higher than a setting temperature. Consequently, heat is rejected at the external condenser and input power of compressor is lower than that of the single circuit of refrigerant.

INTRODUCTION

Traditionally, conventional hot air dryers are used for drying agricultural products. However, conventional hot air drying uses high drying air temperature, which results in low product quality. In previous research, it was found that the quality of agricultural products, dried by heat pump, was better than the quality of those dried by conventional hot air dryers (Rossi et al. 1992). Heat pump drying can use low drying air temperature due to the dehumidification effect at the evaporator. Furthermore, heat pump drying is energy efficient because both sensible heat and latent heat of air leaving the drying chamber are recovered. Meyer and Greyvenstein (1992) studied economics of using heat pump, electric heater and fuel burner to dry grain. The authors found that a heat pump dryer is more economical system. However, its initial cost is higher than other two systems. Prasertsan and Sean-saby (1998) studied heat pump drying of agricultural products and compared with conventional dryers. They found that the heat pump dryer requires the lowest operating cost but the highest initial cost. Continuous drying of rubber by using heat pump with R12 as a working fluid was studied by Clement et al. (1993). They found that the condition giving maximum specific moisture extraction rate does not correspond to the condition for maximum coefficient of performance of heat pump. The authors suggested to use evaporator bypass air ratio of 60-70% and air mass flow rate of 0.63 kg/s. Achariyaviriya et al. (2000) developed a mathematical model of heat pump dryer using R22 as a working fluid. The authors suggested that the specific air flow rate of 10.3 kg-dry air/h-kg dry papaya and the evaporator bypass air ratio of 85% is the best condition. Nowadays, it has revealed that the refrigerant that used in heat pump causes of ozone depletion and global warming whereas the people are demanded for the energy conservation. Therefore, the refrigerant R134a is now widely used in a refrigerator.

The purpose of this work is to compare the theoretical performance of heat pump using refrigerant of R134a and R22 and to evaluate the experimental performance of heat pump drying using double circuits of R134a refrigerant and single circuit of R22 refrigerant. In the experimental part, bananas was selected as a testing material. The double circuits of R134a refrigerant was compulsory because the compressor available in the domestic market was small in size. Though, the double circuits heat pump dryer needs higher initial cost, compared to the single circuit, it provides a good potential for minimize energy consumption especially at the stage of low moisture content of drying product.

MATERIALS AND METHODS

The parameters used to study the heat pump system, based on theory, are heating effect, pressure ratio and coefficient of performance of heat pump. In the theoretical analysis, temperature range from 0-20°C at the evaporator and from 45-60°C at the condenser are considered as the operating parameters. In order to simplify the problem, some assumptions are made:

1. The refrigerant at outlet of evaporator and condenser are saturated vapour and saturated liquid, respectively.
2. The compression and the expansion of the refrigerant vapour are an isentropic and an isenthalpic process, respectively.
3. The pressure drop of pipe system is not included.

Figure 1 shows the schematic diagram of the heat pump dryer using single circuit of R22 refrigerant. It comprises of a drying section, 1.3 kW reciprocating compressor, 3.7 kW evaporator, 4.6 kW internal condenser and 2.2 kW external condenser. The evaporator bypass air ratio is fixed at 78%.

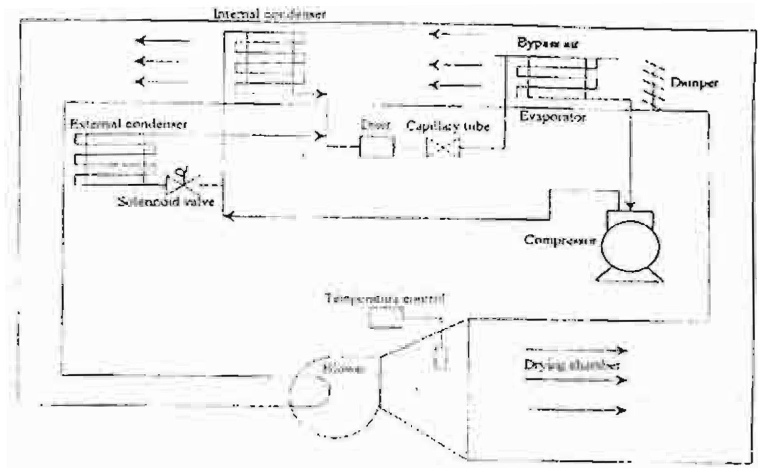

FIGURE 1 The Schematic Diagram of The System Using Single Circuit of R22 Refrigerant.

The schematic diagram of the heat pump dryer using double circuits of R134a refrigerant is presented in Figure 2. Each circuit consists of 0.5 kW reciprocating compressor, 1 kW evaporator and 1.8 kW internal condenser. The external condenser of 1.1 kW is installed in single unit. The evaporator bypass air ratio is fixed at 52%.

The heat pump dryers operate with close air loop. The maximum drying air temperature and the flow rate of air are fixed at 55°C and 0.54 m^3/s, respectively, for all experiments. There are mechanisms of each system to control the drying air temperature when it is higher than a setting point. For double circuits of R134a refrigerant, the excess heat is rejected at an external condenser of an active circuit while another circuit is switched off to reduce input energy in terms of the compressor work. In case of single circuit of R22 refrigerant, the solenoid valve is opened to bypass the refrigerant so as to reject excess heat at the external condenser.

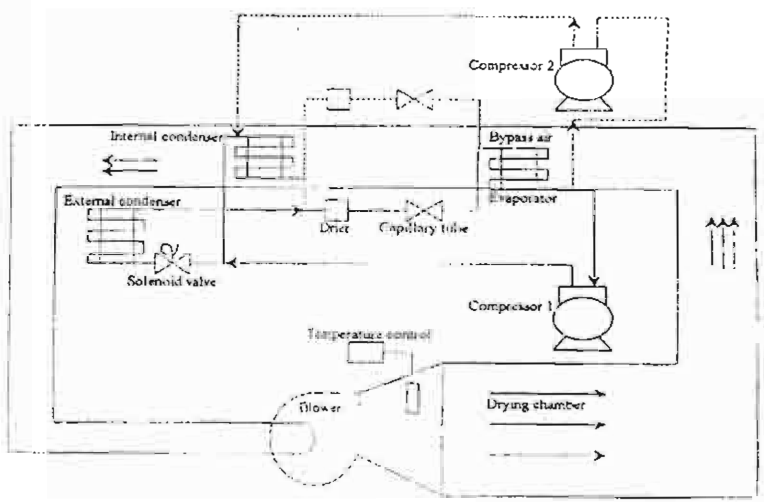

FIGURE 2 The Schematic Diagram of The System Using Double Circuit of R134a Refrigerant.

In the experiments, bananas is selected as a drying product. The moisture content is determined by air oven method at 103°C for 72 hour. The accuracy of a balance was 0.01 gram. The temperatures of the drying air and the refrigerant are measured by type-K thermocouples, connected to a data logger with an accuracy of ±1°C. Air velocity is also measured using a hot wire anemometer with an accuracy of ±4%. In addition, electric energy consumption is measured by both kilowatt-hour meter and a clamp-on meter with an accuracy of ±0.5%. Finally, the refrigerant pressures are monitored using the bourdon gauges.

RESULTS AND DISCUSSIONS

Theoretical Results

The theoretical results are shown in Figures 3, 4 and 5. The heating effect, pressure ratio and coefficient of performance of heat pump are described.

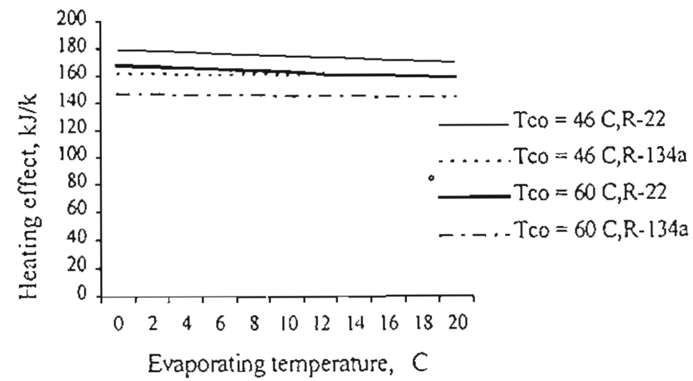

FIGURE 3 The Relationship Between the Heating Effect and the Evaporating Temperature of Working Fluids at Different Condensing Temperature.

Figure 3 shows the relationship between heating effect and evaporating temperature. Base on the same conditions, the heating effect of heat pump using R22 is approximately 8% higher than that using R134a. The decreasing rate of heating effect of heat pump operating on R22 is slightly higher than that of heat pump operating on R134a. However, the heating effect of both heat pumps decreases when the evaporating and/or the condensing temperature increases.

The relationship of pressure ratio and evaporating temperature is shown in Figure 4. The pressure ratio of heat pump using R134a is about 7% higher than that of heat pump using R22. The pressure ratio of both heat pumps decreases when the evaporating temperature increases and/or the condensing temperature decreases.

Figure 5 presents the relationship between the coefficient of performance of heat pump and the evaporating temperature. The COP_h using R22 is slightly higher than that using R134a. The COP_h of both systems decreases when the evaporating temperature decreases and/or the condensing temperature increases.

The heating effect, the pressure ratio and the coefficient of performance of heat pump using R134a are close to those of heat pump using R22 when increasing the evaporating temperature and/or decreasing the condensing temperature.

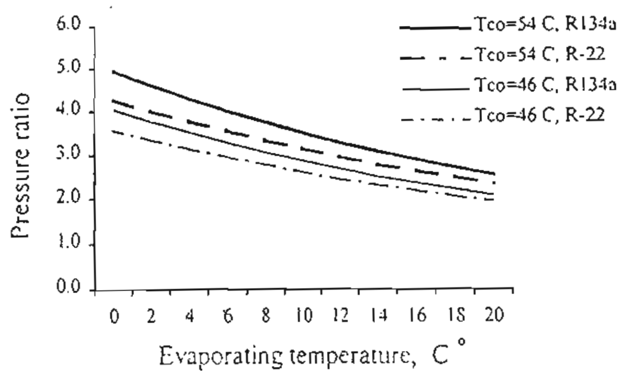

FIGURE 4 The Relationship Between The Pressure Ratio and The Evaporating Temperature of Different Working Fluids at Different Condensing Temperature.

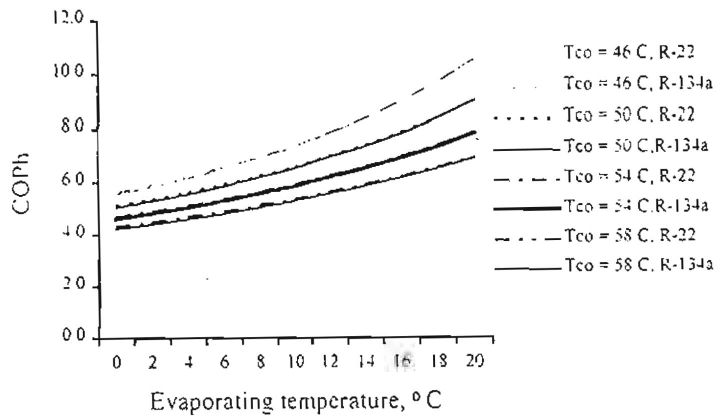

FIGURE 5 The Relationship Between The Coefficient of Performance of Heat Pump and The Evaporating Temperature of Different Working Fluids at Different Condensing Temperature.

Experimental Results

The experimental results are shown in Tables 1 and 2. The temperature gradient along the horizontal direction of the drying chamber decreases with drying time. The variations of air temperature and the air velocity along the vertical direction

of drying chamber are relatively small. Consequently, the average moisture gradient throughout the drying chamber is relatively small too.

The energy is supplied to the system continuously in the forms of work of compressor and blower, providing continuous increment in the drying air temperature of the system. The drying air temperature must be controlled; hence, the excess heat is rejected at the external condenser when the drying air temperature is higher than a setting point. For double circuits of R134a refrigerant, the system switches off one circuit of refrigerant, which is without the external condenser, and rejects the excess heat at the external condenser of the other circuit. As the result of that, half of compressor work is reduced.

TABLE 1 The Experimental Results of Bananas Heat Pump Drying Using Double Circuits of R134a Refrigerant.

Description	Bananas		
	1st	2nd	3rd
Average moisture before drying, % d.b.	251	95	49
Average moisture after drying, % d.b.	92.5	47.0	28.7
Initial weight, kg	72.7	40.2	30.6
Final weight, kg	40.00	30.50	26.20
Moisture removed, kg	32.7	9.70	4.40
Average drying temperature, °C	52	54	54
Average compressor work, kW	1.16	0.92	0.70
Average power consumption, kW	1.80	1.55	1.25
Energy consumption, kWh	27.07	21.77	16.25
Drying time, h	15	14	13
Drying rate$_{avg}$ kg water evap. / h	2.18	0.69	0.34
SMER$_{avg}$, kg water evap. / kWh	1.21	0.45	0.27
SEC$_{avg}$, MJ / kg water evap.	2.98	8.08	13.30
Average condensing temperature, °C	56	57	57
Average evaporating temperature, °C	20	21	20
Average pressure ratio (theory)	2.67	2.65	2.74
Average pressure ratio (experiment)	3.1	3.4	3.7
Average COPh (theory)	6.7	6.6	6.0
Average COPh (experiment)	4.3	4.1	4.1

In case of single circuit of R22 refrigerant, the excess heat is rejected at the external condenser while the input power of compressor is not reduced. Thus, the quantity of waste heat of a dryer using single circuit is higher than that of a dryer using double circuits of refrigerant.

The testing results of the system using double circuits of R134a refrigerant shown that the first stage of bananas drying has the highest energy consumption whereas the third stage of bananas drying has the lowest energy consumption. The reduction of energy consumption can be explained by the fact that the initial moisture content of bananas at the first stage is high, thus the system switches on both compressors all the time. The moisture content of bananas at third stage is the lowest, therefore the drying air temperature is increased to the setting point more rapidly than the other stages. Consequently, the system operates single unit at this stage and less energy is needed. Although, the drying time of each stage is slightly varied, the energy consumption is significantly reduced. The testing results of the system using single circuit of R22 refrigerant shown that the input power of compressor is constant throughout the drying time; hence the energy consumption of the system is not reduced.

TABLE 2 The Experimental Results of Bananas Heat Pump Drying Using Single Circuit of R22 Refrigerant.

Description	Bananas	
	1st	2nd
Average moisture before drying, % d.b.	287.0	186.0
Average moisture after drying, % d.b.	133.0	57.8
Initial weight, kg	98.2	59.5
Final weight, kg	59.30	39.25
Moisture removed, kg	38.90	20.25
Average drying temperature, °C	52	55
Average compressor work, kW	1.39	1.42
Average power consumption, kW	1.96	1.97
Energy consumption, kWh	39.1	69.0
Drying time, h	20	35
Drying rate$_{avg}$ kg water evap. / h	1.95	0.58
SMER$_{avg}$, kg water evap. / kWh	0.99	0.29
SEC$_{avg}$, MJ / kg water evap.	3.62	12.3
Average condensing temperature, °C	56	57
Average evaporating temperature, °C	19	16
Average pressure ratio (theory)	3.22	3.50
Average pressure ratio (experiment)	3.73	4.36
Average COPh (theory)	6.1	5.6
Average COPh (experiment)	4.5	4.3

For both systems (See comparative figures of average power consumption in Tables 1 and 2), the specific moisture extraction rate decreases whereas the specific energy consumption increases at next stages. This is due to the decrease of moisture content of bananas with time. Therefore, the quantity of moisture removed at the next stages is less than the previous stages whereas the input power is not reduced.

It should be noted that the effect of pressure drop is not included in the theoretical analysis, thereby, the experimental pressure ratio is higher than the theoretical pressure ratio. Consequently, the experimental coefficient of performance of heat pump is lower than that obtained by theoretical analysis.

CONCLUSION

The theoretical results show that the heating effect and coefficient of performance of heat pump of system operating on R22 are 8% and 1%, respectively, relatively higher than that operating on R134a. The pressure ratio of system using R134a is 7% higher than that using R22. The performance of heat pump dryers using single circuit of R22 refrigerant and double circuits of R134a refrigerant are investigated. For the heat pump dryer using double circuits of refrigerant, the energy consumption of the heat pump dryer can be reduced by switching off one circuit of refrigerant when a setting temperature is reached.

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New Technology for Transport of Fruits and Vegetables

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Keywords: fresh produce, optimum transport temperature, humidity, respiriation gas control, airflow, Advanced Fresh Air Management, Variable Freqency Drive

Abstract

The number one factor in preserving fresh fruits and vegetables post harvest is temperature. Both the time taken to get the products to their optimum transport temperature, and the maintenace of that temperature throughout the load and over the transit time to market. Secondary factors are humidity and respiriation gas control during the time in transit.

New technologies are in place that monitor, maintain and record levels of CO_2 and O_2 created by the natural process of respiration on harvested products. These technologies also impact the issue of humidity control in a positive manner. The result of these technologies is to provide quicker product temperature pull-down, protection of products from respiration gas damage, and maintenance of benefical levels of respiration gases during transit to market.

Thermo King Corporation has developed these new technologies as options to the existing line of container refrigeration equipment. The first patented option is called AFAM +, which stands for ADVANCED FRESH AIR MANAGEMENT. This system utilizes a motorized fresh air exchange system, CO_2 and O_2 sensors to control the respiratin gases produced naturally by produce in transit. This system can maintain gas levels as desired by making fresh air exchange dynamic, chaning as required to provide a save and beneficial gas level. When the fresh air exchange is not initiated until required by gas levels, quicker product pull-down is achieved, and fewer defrosts are required, providing a humidity enriched environment where required.

The second option patented by Thermo King is VFD, or VARIABLE FREQUENCY DRIVE. This option modulates the speed, therefore airflow, of the evaporator fans in the refrigeration equipment based on product requirements. When the product is in the pull-down stage, the fans operate at 60 hz, even when the base power supply is 50 hz. As the product reaches appropriate transport temperature, the fans slow down, lowering fan speed accordingly. This process provides less transpiration of water from the product, and provides a naturally produced, high humidity environment as required.

These two new options provide excellent opportunity for enhanced product out-turns of fresh fruits and vegetables.

Recent Research and Development Work on Paddy Drying in South-East Asia

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Keywords : paddy drying, fluidised-bed dryer, in-store dyer, rice husk furnace

Abstract

For more than a decade, research on paddy drying has been conducted in ASEAN countries especially Thailand, Vietnam and the Philippines, in collaboration with the Australian Center for International Agricultural Research. Recently, the Japan International Research Center on Agricultural Sciences has been co-operating with Thailand to conduct research for reducing post-harvest losses of paddy. Most of the work done and being done concentrates on rapid drying by using fluidisation and spouted bed techniques, as well as slow drying in storage or in-store drying. In addition, a lot of effort has been directed to the development of a rice husk furnace, especially that incorporating the cyclone concept.

The fluidised-bed paddy dryer was commercialized in 1995 and has been sold to several countries, including Thailand, Malaysia, Indonesia, the Philippines, Taiwan, Myanmar, Laos, Spain, Guyana etc. More than 100 units have been sold so far. The cyclonic rice husk furnace was also been commercialised in 1998 and almost 100 units have been sold in several countries. The practice of in-store drying of paddy has been accepted in rice-mills in Thailand, though it is not very popular due to the requirement for long-term storage. Some rice-mills use the technique for aeration of bulk stored paddy in order to replace grain-turning, which has been practiced since very long time.

IT has been suggested that high moisture paddy should be dried quickly to approximately 23% moisture content (dry basis[1]) and then subjected to slow drying with ambient air during storage (Soponronnarit *et al.*, 1994; Driscoll and Srzednicki, 1991). Following two-stage drying, cost and product quality appear to be optimised. In this paper, fast drying using techniques of fluidised bed and spouted bed, slow drying in storage using ambient or near-ambient air and the rice husk furnace, which has become increasingly popular, are discussed.

Fluidised Bed Paddy Drying

Fluidised bed paddy drying is an alternative to conventional hot air drying. Its advantages are: (1) uniform product moisture content, and thus high drying air temperature can be employed but with less over-dried grain; (2) high drying capacity due to better heat and mass transfer; (3) a much smaller drying chamber and thus a significantly lower initial cost; and (4) significant spin-off in terms of increasing head rice yield and potential for producing aging rice.

History

Sutherland and Ghaly (1992) were probably the first research group to investigate the feasibility of using fluidisation technique for paddy drying. Experimental results showed that head yield was 58-61% when paddy was dried from 28.2 to 20.5% but was 15-24% when the final moisture content was 19%. Tumambing and Driscoll (1993) found that drying rate was affected by drying air temperature and bed thickness under experimental conditions as follows: drying air temperature of 40-100°C; bed thickness of 5-20 cm and air velocity of 1.5-2.5 m/s. They also developed a mathematical model for continuous fluidised bed paddy dryer.

[1] Unless otherwise stated, the moisture contents (m.c.) quoted in this paper are dry basis.

Soponronnarit and Prachayawarakorn (1994) reviewed research and development work on fluidised bed drying of grain, and conducted both experimental and simulation studies on batch fluidised bed paddy drying. Soponronnarit *et al.* (1996a) described the development of a cross-flow fluidised bed paddy dryer with a capacity of 200 kg/hour. Experimental results showed that final moisture content of paddy should not be lower than 23% if quality in terms of both whiteness and head yield were to be maintained. Drying air temperature was 115°C. Simulation results indicated that the appropriate operating parameters should be as follows: air speed, 2.3 m/s; bed thickness, 10 cm; and fraction of air recycled of 0.8. With these conditions, energy consumption was close to the minimum, while drying capacity was near maximal. In this study, moisture of paddy was reduced from 30 to 24%. Following the success of the development of the cross-flow fluidised bed paddy dryer, Rice Engineering Supply Co. Ltd., a private company in Thailand, showed interest in collaborating in the development of a prototype with a capacity of approximately 1 t/hour (Soponronnarit *et al.*, 1995a). The prototype is similar to the later-developed commercial unit shown in Figure 1. It comprises a drying section, a 7.5 kW backward curved blade centrifugal fan, a diesel fuel-oil burner, and a cyclone. The bed length, width and height of the drying section are 1.7, 0.3 and 1.2 m, respectively. Depth of the paddy bed is controlled by a weir. Paddy is fed in and out by rotary feeders. In operation, hot air (temperature controlled by thermostat) is blown into the drying section through a perforated steel sheet floor. The air and grain flows are perpendicular to each other. A small portion of the air leaving the drying chamber is vented to the atmosphere, while the remainder, after cleaning in a cyclone, is recycled to the dryer, mixed with ambient air and reheated to the desired temperature. Feed rate of paddy can be varied from less than 1 t/hour to more than 1.5 t/hour. Experimental results showed that the unit operated efficiently and yielded high product quality, in terms of head yield and whiteness. In reducing the moisture content from 45 to 24%, using air temperature of 100-120°C, fraction of air recycled of 0.66, specific airflow rate of 0.05 kg/s-kg dry matter, superficial air velocity of 3.2 m/s, and bed depth of 0.1 m, total primary energy consumption was 2.32 MJ/kg of water evaporated. Of this, 0.35 was primary energy from electricity (electrical energy multiplied by 2.6) and 1.79 was primary energy in terms of heat energy.

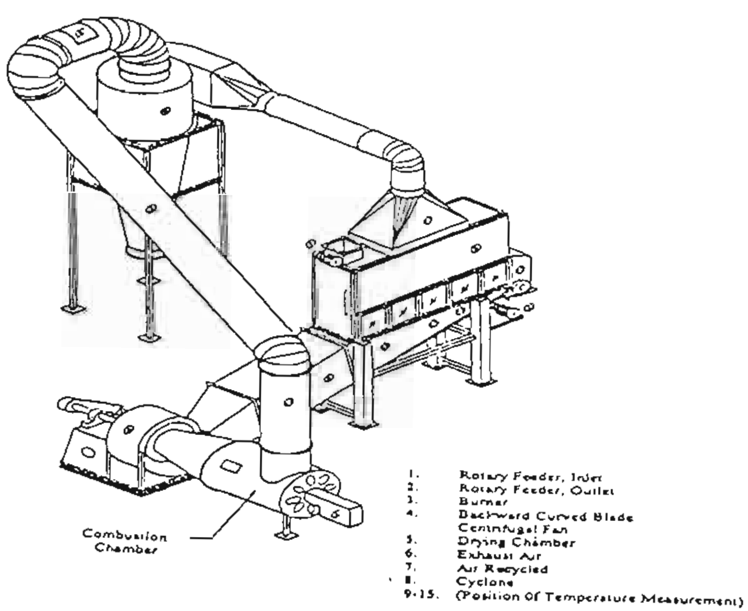


Fig. 1 Commercial fluidised bed paddy dryer

As a result of the success of the prototype, commercial fluidised bed paddy dryers with capacities of 5, 10 and 20 t/hour as shown in Figure 1 are now available. More than 100 units have been sold since the beginning of 1995. The fluidised bed dryer is composed of a drying chamber, a backward curved blade centrifugal fan, a burner using diesel oil or fuel oil for heating air, and a cyclone. A commercial cyclonic rice husk furnace is now available. More than 80 units have been sold since the beginning of 1998.

Minimum fluidised bed velocity

From the experimental results reported by Soponronnarit and Prachayawarakorn (1994), the minimum fluidised bed velocity for paddy is approximately 1.6 m/s and increases with moisture content. The relationship between pressure drop across the paddy bed and bed velocity is presented in Figure 2.

For maize, the minimum fluidised bed velocity increases with moisture content. It varies from 1.5 to1.8 m/s as reported by Soponronnarit *et al.* (1997a). For soybean, Soponronnarit *et al.* (2000a) reported that the minimum fluidised bed velocity is 1.9 m/s and varies slightly and inversely with moisture content.

Experimental results from commercial fluidised bed grain dryers

Experimental results from commercial fluidised bed paddy dryers with capacities of 2.5-5 t/h and 5-10 t/h are summarized in Table 1 (Soponronnarit *et al.*, 1996b). Paddy qualities, in terms of head yield and whiteness, are all acceptable when compared to paddy dried by ambient air (reference) which is expected to obtain highest quality. Energy consumption is relatively low, compared to conventional hot air dryers, except with low inlet paddy moisture content. It is generally recommended to dry paddy from high moisture level to a moisture content of approximately 23% in order to maintain paddy quality. However, it is possible to dry paddy to a lower moisture level if a tempering process is used after the fluidised bed drying. In addition, head yield can be greater than with ambient air drying if proper drying conditions are provided. The effects of both tempering and drying on paddy quality will be presented in the next section.

Effects of drying, tempering and ambient air ventilation on moisture reduction and quality of paddy

Soponronnarit *et al.* (1999) investigated the management of moist paddy by three consecutive processes, i.e., fluidised bed drying, tempering and ambient air ventilation. Experimental results showed that, after the three processes, moisture content is reduced from 33% to 16.5% within 53 minutes. During the first process, a fluidised bed dryer, with inlet air temperature of 150°C, reduced the moisture content of paddy down to 19.5% within 3 minutes. The paddy was then tempered for 30 minutes. Finally, it was cooled by ambient air, at

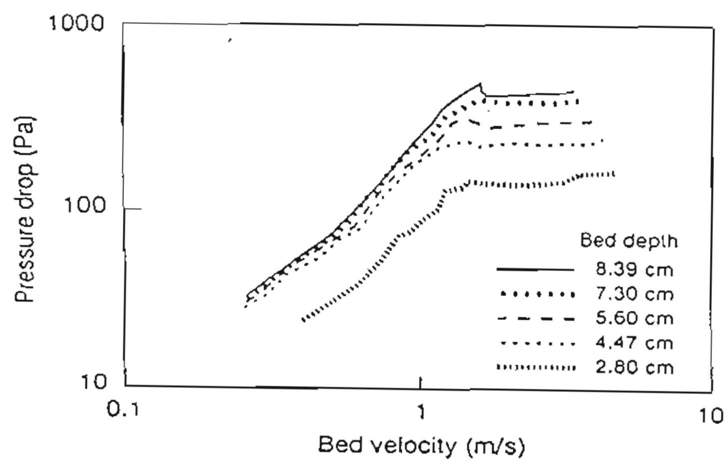


Fig. 2 Relationship between bed pressure drop and bed velocity at different bed depths in fluidised bed paddy dryer

Table 1 Performance test results of commercial fluidised bed paddy dryers

Testing results	Test no. 1	2	3	4	5
Drying air temperature (°C)	115.0	116.0	120.0	130.0	150.0
Drying air recycled (%)	69.0	69.0	69.0	69.0	53.0
Inlet moisture content of paddy (% dry basis)	22.0	26.0	28.7	30.6	27.0
Outlet moisture content of paddy (% dry basis)	20.1	22.5	22.5	23.0	21.0
Outlet paddy temperature (°C)	54.0	52.0	54.0	57.0	63.0
Electrical energy consumed (MJ/kg-water evap.)	0.83	0.43	0.26	0.21	0.15
Thermal energy consumed (MJ/kg-water evap.)	7.80	3.13	2.57	2.21	3.90
Head rice yield (%)					
- dried in fluidised bed dryer	53.2	54.3	53.9	57.0	48.1
- dried by ambient air (reference)	57.4	57.2	53.9	57.0	56.2
Rice whiteness					
- dried in fluidised bed dryer	40.3	40.7	40.0	43.7	36.8
- dried by ambient air (reference)	44.4	44.2	40.1	43.8	42.6
Testing hours	5.0	35.0	46.0	51.0	29.0
Drying capacity (tons/h)	9.5[b]	9.5[b]	9.5[b]	9.5[b]	4.8[a]

Remarks. a = Dryer with capacity of 2.5 – 5.0 tons/h
b = Dryer with capacity of 5.0 – 10.0 tons/h

30°C and 55-60% RH, at a speed of 0.15 m/s for 20 minutes. Quality of paddy in terms of head rice yield and whiteness is acceptable.

Spin-off from fluidised bed paddy drying

Soponronnarit *et al.* (1998) conducted paddy drying using fluidisation technique and paddy tempering following drying in a laboratory and found a significant spin-off. Head yield increased to more than 50% when paddy is dried by fluidisation technique with inlet drying air temperature of 140-150°C and initial moisture content of paddy of 29.9 - 44.9%. As initial moisture content increases, head rice yield increases. Final moisture contents of paddy that can increase head yield to a maximum value are in a range of 23.4 - 28.2%. It is believed that gelatinization, especially at the surface of rice kernel, is the main factor for increasing head yield. Tempering of paddy after drying can maintain head yield. Rice whiteness of dried paddy is mostly acceptable, provided that the tempering temperature is not higher than 60°C. For consumer acceptance, tested rice without tempering is not significantly different from that dried by ambient air, while tested rice with tempering, after being cooked, has higher bad smell and lower whiteness. However, this may be solved by reducing tempering time down to 30 minutes. This issue requires further research.

For other grains, the fluidised bed dryer has a great potential for commercialization. More than ten units have been used in parboiled rice, maize and animal feed (for eliminating trypsin inhibitor) industries. Experimental results obtained from commercial fluidised bed dryers showed good performance and good product quality with a significant spin-off that urease activity in soybean kernel could be reduced to an acceptable level required by animal feed industry.

Spouted Bed Dryer

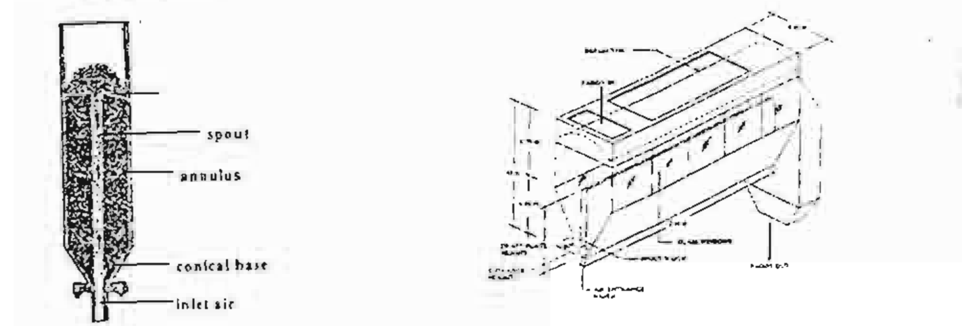
The spouted bed technique is an alternative to fluidisation, for drying grains that are too coarse and non-uniform in size. The conventional spouted bed shown in Figure 3a has a conical-cylindrical shape (Mathur and Epstein, 1974). Drying air, with a sufficiently high velocity, is introduced through a centrally located small opening at the conical base,

causing grains to rise rapidly through a hollow central core, called the spout zone, within the vessel. These grains, after rising a certain height above the bed surface, separate from the air stream and drop into the annulus region. In this region, grains move slowly downward. Some portions of these grains may be re-entrained into the spout region before reaching the bottom, where the mixing of particles is very rigorous. The cyclic and spout patterns are a very important characteristic of the spouted bed. However, the conventional spouted bed dryers have not been available for industrial applications due to the problems of scaling-up and control of cyclic pattern. To overcome such limitations, a modification has been made by inserting draft plates between the annulus and spout regions. The modified spouted bed dryer is shown in Figure 3b showing that the cyclic movement for grains is improved, comparing to Figure 3a, while the spout characteristic is still maintained (Madhiyanon *et al.*, 2001; Hung-Nguyen *et al.*, 2001). The spout and annulus regions that separate definitely by draft plates provide the advantage for drying the heat-sensitive particulate solids in particular paddy, corn and soybean etc. but the drying capacity is lower under the same drying conditions The slow drying rate in the annulus region may reduce the stress inside the grains, thus obtaining the better quality of grains. Madhiyanon *et al.* (2001) conducted the paddy drying experiments in a spouted bed dryer with draft plates. The results are summarised in Table 2.

Thermal energy consumption, in the range of 3.1-3.8 MJ/kg water evaporated at an approximate drying capacity of 3000 kg/h, is comparable to the commercial dryer shown in Table 1. Head rice yield after drying in the spouted bed dryer is reduced approximately 1% compared to the sample before drying whilst the reduction in head rice yield from the fluidised bed is higher. In addition to higher head rice yield, the rice whiteness is also better. In spite of superior quality of paddy, the spouted bed dryer has not been fully commercialised. This may be because of the relatively low drying rate for this dryer.

In-Store Drying

In-store drying, also known as fixed bed grain



a) Conventional spouted bed (Mathur and Epstein, 1974)

b) Draft plate spouted bed (Madhiyanon et al., 2001)

Fig. 3 Schematic diagram of spouted bed dryers

For the draft plate spouted bed, drying mostly takes place in the spout region since grains are exposed to high air velocity and high temperature whilst drying in the annulus, where the grains and the air move in the opposite direction, is rare because of low air velocity (Hung-Nguyen *et al.*, 1998). Water evaporation occurring in this dryer results in a higher thermal efficiency compared to the fluidised bed, drying, can be suitably applied for the relatively low initial moisture contents of grains, 22-25% dry basis (Soponronnarit *et al.*, 1995b). This technique offers the superior grain quality and effective heat utilisation. Figure 4 shows an in-store drying system comprising a bin, heater unit and ventilation system.

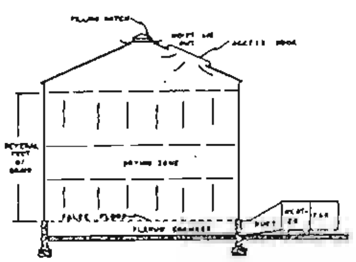


Fig. 4 In-store Drying system (Brooker *et al.*, 1992)

The drying zone starts at the bottom and then moves upwards. A low airflow rate is often used in order to avoid a large pressure drop in the bed. For drying paddy with an initial moisture content between 20% and 22% dry basis under the hot and humid weather, the ambient airflow rate should be in the range between 0.5 and 1.0 $m^3/min\text{-}m^3$ of paddy and the relative humidity should not be higher than 75% (Soponronnarit *et al.*, 1995b). The air may need to be slightly heated when severe air conditions are encountered. This ensures that already dried paddy will not adsorb water vapour from the humid air. If the paddy adsorbs water, it may reduce grain strength (Kunze, 1995). In addition, high inlet humidity may cause moisture migration within the grain bulk. This may also occur naturally during the long-term storage, caused by gradient of temperatures. Proper ventilation can prevent this.

Soponronnarit *et al.* (1997b) studied the field trial of in-store drying and storage using ambient temperature and an airflow rate of 0.57 $m^3/min\text{-}m^3$ of paddy. During the 19-week storage, air ventilation was done twice a week, for at least 2 or 3 hours each time. Moisture migration was not found and paddy quality, in terms of whiteness and head rice yield obtained, did not change.

Another quality index of commercial interest, besides head rice yield, is rice yellowing. Rice yellowing is a serious problem in the tropics. Trashing and drying delays may cause yellowing (Mendoza and Rigor, 1982). Yellow kernels were found in paddy having a moisture content of greater than 25% dry basis, corresponding to a water activity of 0.96. Such conditions would promote rapid micro-organism growth when grains were then heated up to temperatures between 45 and 60°C. Phillips *et al.* (1989) noticed that kernels at the central area of paddy bulk, where high temperature exists, had an intense yellow within 2-3 days, whereas grain at the bulk surface showed fewer yellow kernels. The mechanism of yellowing is not fully understood, although despite a large number of investigations. A summary of previous work would suggest that yellowing of paddy is due to metabolic activities of microbes and non-enzymatic browning or the Millard reaction (Quitco, 1982; Indudhara Swamy *et al.*, 1971; Yap *et al.*, 1988). Whatever the cause, moisture content and temperature are important factors contributing to the degree of yellowness. Yellowing of rice produced inside the kernels is not uniform, degree of yellowness decreasing from the surface to the inner layers (Yap *et al.*, 1988).

Recently, quantitative studies of the influences of water activity, temperature and storage atmosphere on yellowing of paddy have been carried out. Some workers (Gras *et al.*, 1989; Bason *et al.*, 1990) reported that water activity and temperature strongly affected the degree of yellowness whilst O_2 was less significant. The yellowing kinetic formulated by Gras *et al.* (1989) was described by the following power law model: $k = \alpha . e^{\beta'/T}(a_w)^{\gamma}[O_2]^{\delta}$, where k is rate of yellowing (Hunter b unit/day), T is absolute temperature (K), a_w is water activity, O_2 is oxygen content (mol/m^3) and δ, β, α and γ are constants. By contrast, Soponronnarit *et al.* (1998) found yellowing rate followed with a zero order kinetic model, $\ln k = \alpha - \delta a_w - \varepsilon/T + (\gamma a_w)/T$ where δ, ε, α and γ are constants.

Rice Husk Furnace

Singh *et al.* (1980) designed and tested a cyclonic rice husk furnace for drying one tonne of paddy with initial moisture content of 35% down to 14% dry basis. Efficiencies of the furnace were different at various rice husk feed rates and air flow rates. Highest efficiency was 80% with a rice husk feed rate of 20 kg/h and air flow rate of 168 m^3/h. Tumambing (1984) investigated the performance of the cyclonic rice husk furnace of Padicor for paddy drying and found that combustion efficiency was 98%. Xuan *et al.* (1995) designed and tested two types of rice husk furnace. The first one was a furnace with inclined grate and cylindrical combustion chamber. The upper part of the furnace was a heat exchanger. Inlet air entered the lower part of an inclined grate on which rice husk with a feed rate of 20-25 kg/h was burnt. Furnace efficiency was 70%. The second type was a pneumatic-fed cyclonic furnace. It consisted of combustion chamber and rice husk feed system. Rice husk was fed into the combustion chamber with primary air and burnt. Then it fell down to the lower part of the chamber. Secondary air entered at the upper part of the combustion chamber in a tangential direction, in order to eliminate dust from flue gas. Rice husk consumption and furnace efficiency were 10-12 kg/h and 75%,

Table 2 Summary of paddy drying experiments in the industrial-scale spouted bed dryer (Madhiyanon *et al.*, 2001)

	Test No.							
Description	8[a]	9[b]	10[b]	11[c]	12[c]	13[c]	14[c]	15[d]
Feed rate (kg/h)	2470	2440	1990	2370	2400	3160	3280	3550
Hold-up (kg)	60	360	340	240	210	335	290	310
Residence time (min)	1.5	8.9	10.2	6.0	5.3	6.4	5.3	5.2
Average inlet air temp. (°C)	154	149	141	152	159	154	156	160
Exit grain temp. (°C)	68	71	66	71	68	67	67	68
Average moisture content								
BFD (% dry basis)	26.1	21.7	28.5	22.1	25.0	29.4	28.2	22.8
AFD (% dry basis)	22.7	17.5	23.6	17.1	19.7	25.0	23.3	19.0
Head rice yield								
BFD (%)	56.1	45.9	53.3	49.0	49.6	50.1	54.3	41.2
AFD (%)	58.9	45.7	54.2	47.4	48.4	52.4	55.0	40.8
Whiteness								
BFD	41.9	45.7	44.2	47.6	47.6	47.8	46.4	46.7
AFD	41.6	45.4	45.0	46.8	46.7	47.5	46.3	45.9
Drying rate (kg water/h)	68	87	79	101	106	111	130	101
Energy consumption (MJ/kg water evaporated)								
Heat	6.5	7.0	N/A	4.4	5.2	3.5	3.8	3.1
Electricity	0.60	0.60	0.60	0.50	0.50	0.46	0.40	0.46

AFD after drying; BFD, before drying; N/A, not available; temp., temperature.
[a] Draft channel blade angle 85°; entrance height, 10 cm.
[b] Draft channel blade angle 89°; entrance height, 10 cm.
[c] Draft channel blade angle 89°; entrance height, 12.5 cm.
[d] Draft channel blade angle 89°; entrance height, 15 cm.

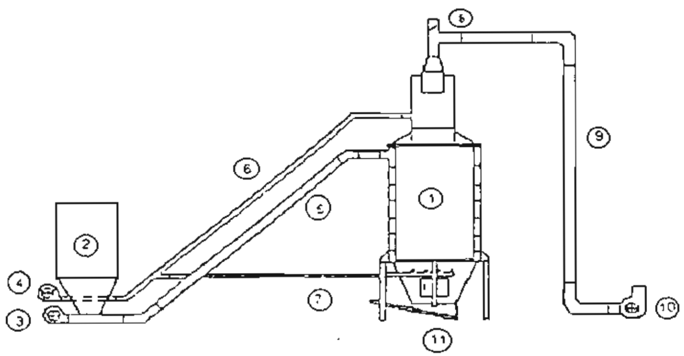
respectively. Past research showed that there were several designs of rice husk furnace, i.e. vortex or inclined grate types and direct use of flue gas or indirect use of thermal energy from combustion via heat exchanger. However, acceptance of the furnace was still limited to experimental sites.

Soponronnarit *et al.* (2000) developed a commercial-scale prototype of cyclonic rice husk furnace for a commercial fluidised bed paddy dryer with a capacity of 10 tons/h, as shown in Figure 5. The furnace consisted of a combustion chamber, feeding systems of air and rice husk, a control system and a suction blower. The combustion chamber was made of steel in cylindrical shape with inner and outer diameters of 1.37 and 1.76 m, respectively, and height of 2.75 m. Materials inside the combustion chamber, at the lower part from inner layer to outer layer, were the following: fire brick, steel, glass fiber and covering steel. There was a grate with diameter of 1.37 m, thickness of 9.5 mm (583 holes/m^2, hole diameter = 0.0127 m) and ash paddle with cross-section 50 x 50 mm and length 1.1 m at the lower part of combustion chamber. The primary air duct was connected to the upper part of the combustion chamber in tangential direction. On the upper part of the combustion chamber, a steel cylinder with inner diameter of 0.8 m and height of 1.6 m was installed and connected to the secondary air duct in tangential direction in order to clean up flue gas. The cylinder was insulated with cement 60 mm thick. Rice husk ash was removed from the combustion chamber by the ash paddle followed by a screw conveyor installed under the combustion chamber. The tertiary air duct was connected to the bottom part of the combustion chamber in order to support complete combustion. The rice husk feeding system consisted of a rice husk hopper with a screw installed at the bottom and driven by a 0.37 kW motor, a 0.152 m diameter primary air duct for pneumatic feed of rice husk and a fan. The secondary air duct was 0.102 m in diameter. The tertiary air duct with diameter of 0.076 m separated from the secondary air duct and then was divided into 4 ducts with distributors at the bottom of the combustion chamber under the grate. The air suction system consisted of a 15 kW blower, a duct with diameter of 0.254 m and a valve for regulating the fraction of fresh air into the combustion chamber.

The experimental results showed that, for heights of ash on grate 30, 45, 50 and 60 cm, rice husk feed rates 110-136 kg/h, and excess air 265-350%, the combustion gas temperature was approximately 523-710°C. Thermal efficiency of the furnace system increasing with excess air was approximately 57-73% while carbon conversion efficiency was approximately 89-97%. The height of ash on grate had no effect on the system performance. Financial analysis indicated that the pay-back period of the furnace was 1200 hours, when using in place of the diesel oil burner. Latest information shows that the rice husk furnace was commercialized in 1998 and almost 100 units have been sold in several countries.

Conclusions

The first fluidised bed paddy dryer was commercialized in Thailand in 1995. It is probably the first commercial, large-scale, continuous fluidised bed dryer for paddy drying. Since then, more than 100 units, with capacities of 5, 10 and 20 t/hour have been sold in Thailand, the Philippines, Indonesia, Malaysia, Myanmar, Laos, Spain, Guyana and Taiwan. Due to high operating costs for using diesel oil, the rice husk furnace has become increasingly popular. The cyclonic rice husk furnace, as illustrated in this paper, has been commercialized and almost 100 units sold in several countries since the beginning of 1998. The fluidised bed paddy dryer is competitive with conventional hot air dryers especially at high moisture level, having low energy consumption, low cost and acceptable paddy quality. Important operating parameters are: a drying air temperature of 140 - 150°C, the fraction of air recycled of 0.8, an air velocity of around 2.0 - 2.3 m/s and bed thickness of 10 - 15 cm. Under proper conditions, such as high initial moisture content of paddy (higher than 29.9%) and high air temperature (140 - 150°C), head yield can be increased up to 50% compared to ambient air drying. For consumer acceptance, tested rice with fluidised bed drying is not significantly different from that dried by ambient air.



1 combustion chamber
2 rice husk hopper
3 conveying fan of rice husk feeding system
4 conveying fan of air feeding system
5 primary air duct
6 secondary air duct
7 tertiary air duct
8 butterfly valve
9 exit air duct
10 suction blower
11 screw conveyor

Fig. 5 Schematic diagram of the cyclonic rice husk furnace

Spouted bed paddy drying has been researched in the ASEAN region, especially in Thailand and Vietnam. It could provide an alternative to fluidised bed drying, but the advantages of using spouted bed technique are not very clear. As a result, it has not been commercialised yet.

In-store paddy drying has only been used in a limited number of rice mills in Thailand, due to the requirement of long term storage, in spite of its low energy consumption and high quality product of

head rice yield. However, this technique has been used successfully in several rice mills for aeration of bulk stored paddy instead of grain turning.

Acknowledgements

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Session 1

Maintaining Quality of Perishable Produce

Sukprakarn, C., S. Ruay-Aree, G. Srzednicki, B. Longstaff, B. McGlasson, A. Hocking, J. Van, S. Graver, A. Wongkobrat and P. Visarathanonth, eds. 2002. Quality management and market access. Proceedings of the 20th ASEAN/2nd APEC Seminar on Postharvest Technology, Lotus Hotel Pang Suan Kaew, Chiang Mai, Thailand, 11-14 September 2001. 540 pp.

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- 1 Paddy (Suphanburi 2) (photo : Rice Research Institute, Bangkok, Thailand)
- 2-3 Fruits and vegetables in market, Bangkok (photo : M. Kongchuensin)
- 4 Fluidised bed dryer (photo : S. Soponronnarit)

Quality Management and Market Access

Proceedings of the 20th ASEAN/2nd APEC Seminar
on Postharvest Technology

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Comparative Experiment on Drying of Brown Rice and Paddy Using Heat Pump and Hot Air Dryers

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Keywords: brown rice, drying kinetics, paddy, rice quality

Abstract

The objective of the present work is to compare the drying rate and the quality attributes of rice such as whiteness and head rice yield for brown rice and paddy using heat pump and conventional hot air dryers. The experiments have been carried out at temperatures between 42 and 50°C and at a specific airflow rate of 5.6 m^3/m^3grain-s. The results have shown that the paddy drying has taken 1.3 - 1.5 times longer than the brown rice drying for reducing moisture content from 23.4% wet basis (wb) to 14% wb. Due to the very complex process of moisture diffusion inside the grain kernel, the empirical thin-layer models have been used to describe the moisture removal in brown rice and paddy. The chosen Lewis and Page equations can accurately predict the experimental data. The constants obtained by using a non-linear least-square technique are related to the temperature. The results of the relative head rice yield determination indicate a stronger effect of the temperature on this quality attribute during drying of brown rice than during drying of paddy.

Compared to the hot air dryer, the heat pump dryer provides more powerful capability to reduce the moisture content for the same temperature value of rice whiteness. In contrast, the hot air dryer produces 56-57% higher relative head rice yields.

PADDY is harvested at 18 - 26% moisture content wet basis (wb) and then usually dried to a level that is sufficient to limit microbial growth and biochemical reactions in order preserve its quality to and to extend its shelf life. In general, moisture content of 14% wb is considered appropriate for safe storage and for the subsequent processing.

As already mentioned, drying is an important measure for moist paddy management. A suitable drying technique helps to preserve the quality of grain after drying. The rice processing system generally used in Thailand is shown in Figure 1. Firstly, paddy is dried down to 14% wb by a suitable drying technique practiced in the production area. Drying is followed by husking using a rubber roll husker to produce brown rice. Finally, brown rice is conveyed to a series of mills in order to remove the bran from brown rice surface. The final product becomes white rice.

It was noted that the rubber roll husker had a high efficiency if it was used for paddy with low moisture content. Henderson (1958) and Stripe *et al.* (1972) proposed to reduce the energy consumption for drying paddy by hulling high moisture content paddy before drying, leading to directly transferring heat to paddy surface. This can reduce energy used to move moisture through the husk that can act as a barrier against moisture movement. This also can reduce energy to evaporate moisture from moist husk. Based on these concepts, studies about brown rice drying technique were undertaken by a number of researchers. Henderson (1958) and Stripe *et al.* (1972) studied drying of paddy and brown rice. They found that drying time of brown rice was about 2 times of that of paddy at the same temperature. After drying brown rice would have a radial stress crack. Kunze (1995) described the cause of such cracks as a result of:

(1) the development of stresses inside the kernel due to the phenomenon of moisture re-adsorption
(2) using unsuitable drying conditions, e.g. drying grain at a too high drying rate, causing stress crack inside the kernel.

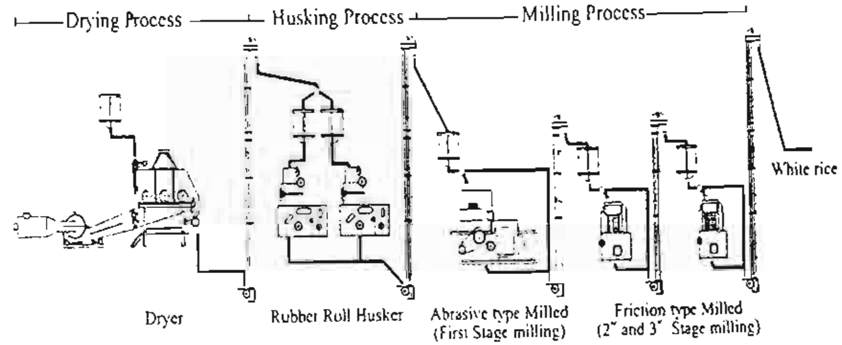

Fig. 1 Typical diagrams of rice processing in Thailand. (Courtesy Rice Engineering Supply Co., Ltd., 2000)

Yamashita (1993) studied drying of brown rice using a heat pump. An impeller husker was used in the experiments. The experimental results were consistent with those of Henderson (1958) and Stripe *et al.* (1972) showing that brown rice was dried more rapidly than paddy and consequently the energy consumption was reduced. An impeller husker has been commercialized in Philippine since late 1970s (Camacho *et al.*, 1978). The suitable rotational speed was found to be about 2000-3000 rpm (Shintada *et al.*, 2000).

Since drying brown rice displays excellent drying kinetics with a subsequent reduction in energy consumption, the objective of this study is to investigate the drying kinetics and quality of brown rice and paddy and to make a comparison between a heat pump and conventional hot air dryers.

Materials and Methods

Materials

In the experiments described in this study a heat pump and hot air dryer were used. The heat pump (Figure 2) is of a closed system type with R-22 used as a working fluid. The main components consist of 4.5 kW inlet and outlet condensers, a 3.7 kW evaporator and forward-curved blade centrifugal fan driven with a 0.75 kW motor. A heat exchanger was installed at the front of evaporator. The hot air dryer is shown in Figure 3. The main component consist of a 0.52 m x .52 m x 0.5 m drying chamber with 0.5 m x 0.5 m trays, a forward-curved blade centrifugal fan driven by a 0.75 kW motor. Three electrical heaters (power of 1 kW of each unit) were installed. The first two units were used for drying and the third unit was used as a temperature controller.

Methods

Sample Preparation

Moisture content of the paddy samples (about 24% w.b.) was adjusted by adding a required amount of water. The wet paddy then stored in a cold room at temperature of 4 - 8°C for 5 - 7 days with thorough mixing every 12 hours to obtain an uniform moisture distribution within the kernel. Brown rice was prepared by hulling the moist paddy by Otaka FKD-38 type impeller husker, in which the rotational speed of impeller was fixed at 1450 rpm.

Drying Experiment

In this work, the drying kinetics of paddy and brown rice dryings using heat pump and hot air dryer were studied. The details of experimental design of each case are shown in Figure 4. Dryings of paddy and brown rice were conducted under the following conditions: specific inlet airflow rate of 5.6 $m^3/s\text{-}m^3$ of paddy or brown rice, drying air temperature of 42-50°C, initial moisture content of paddy and brown rice of 30.5 and 28.1% dry basis (db), respectively.

Drying Equation

In this study, the semi-empirical models, i.e. equations of Lewis (1921) and Page (1952) were

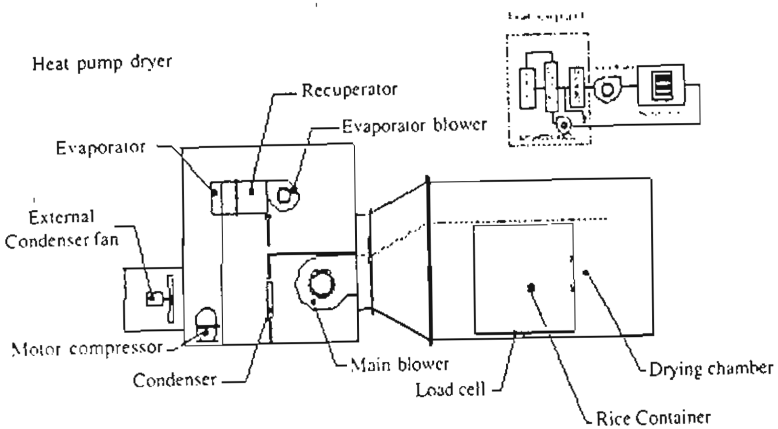

Fig. 2 Heat pump dryer

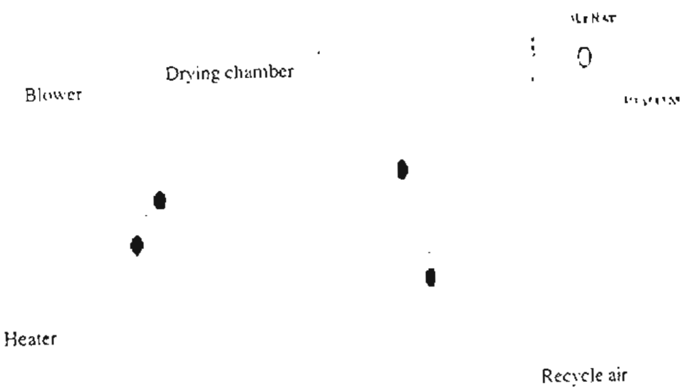

Fig. 3 Hot air dryer

developed. The relationships of these equations are as follows:

Lewis equation $MR = \exp(kt)$ (1)

MR is moisture ratio, t is drying time, min, and k is drying constant (min^{-1}). The latter varied with drying temperature T (°C) and could be calculated from equation (2):

$$k = k_o \exp(-C/T) \quad (2)$$

Page's equation $MR = \exp(-kt^n)$ (3)

Where k is drying constant (min^{-1}), which varied with drying temperature.

k_o, C, and n are drying coefficients.

A non-linear technique was used to estimate the numerical value of the drying coefficients. The fitted models were evaluated by minimising the sum of least square error (R^2). Statistica program was used to obtain the suitable value of drying coefficients, to estimate the best fit with experimental data.

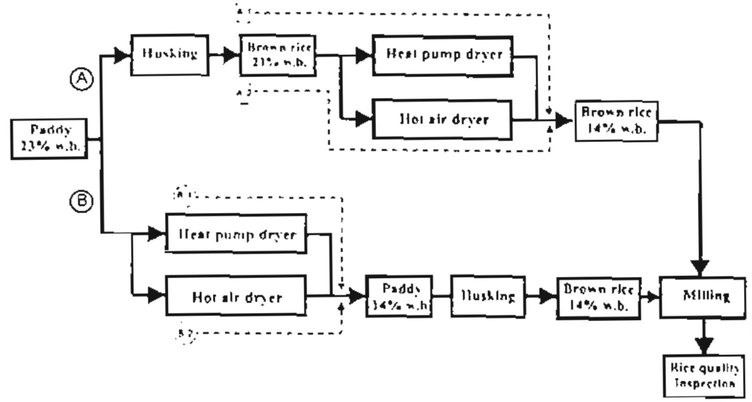

Fig. 4 Flow diagram of the experimental design of paddy and brown rice drying

Rice Quality

After paddy and brown rice were dehusked, dried and milled, quality attributes of rice such as breakage, head rice yield and whiteness were determined. For measurement of the rice whiteness, a Kett-C300 type whiteness meter was used. To study the effects of drying air temperature on head rice yield, the analysis of variance (ANOVA) was used.

Results and Discussion

Drying Kinetics and Drying Equations

The result of curve fitting using least square method shows that Page's equation is more accurate than Lewis' equation. Figure 5 shows that drying of paddy using hot air was slower compared to drying of brown rice, at the same drying temperature. It also illustrates that drying rate increased with drying air temperature. Experimental result of heat pump drying are shown in Figure 6. Similar result to those of hot air drying were obtained. Comparing between drying rate of hot air and heat pump drying, the former yielded slower drying rate for both paddy and brown rice drying, due to higher relative humidity of drying air. It may be concluded that drying time of paddy is 1.3-1.5 times that of brown rice.

Rice Quality

The Effect of Drying Air Temperature on Head Rice Yield

Figure 7 shows the relationship between drying temperature and head rice yields while using heat pump and hot air dryers for paddy and brown rice drying. In case of using the same dryer and drying temperature it was found that head rice yield for paddy was higher than that for brown rice. The analysis of variance (ANOVA) method with the confidence level of 95% showed that paddy drying using hot air dryer and heat pump had no difference in head rice yield. In contrast, brown rice drying using hot air dryer yielded higher head rice yield than when using a heat pump dryer. The difference decreased with the increase of drying air temperature.

Head Rice Yield and Breakage

Figure 8 shows the head rice yield and breakage of brown rice after hulling by impeller husker (B), drying by hot air dryer (C) and milling (D). It was found that, in the stage B, the breakage and head brown rice were 17.8% and 61%, respectively. After drying of brown rice (stage C), the breakage of dried brown rice increased to 18.9-24.8%, depending on drying air temperature. Head yield of brown rice was reduced to 60.1-54.2%. In the milling stage (D), the breakage of milled rice was quit high (29.2-31.2%), while head rice yield was quite low (29.2-31.1%). It may be caused by the effect of drying in stage C, which continually affected the rice breakage and head rice yield in the milling stage (D).

Rice Whiteness

It was found that the rice whiteness of all

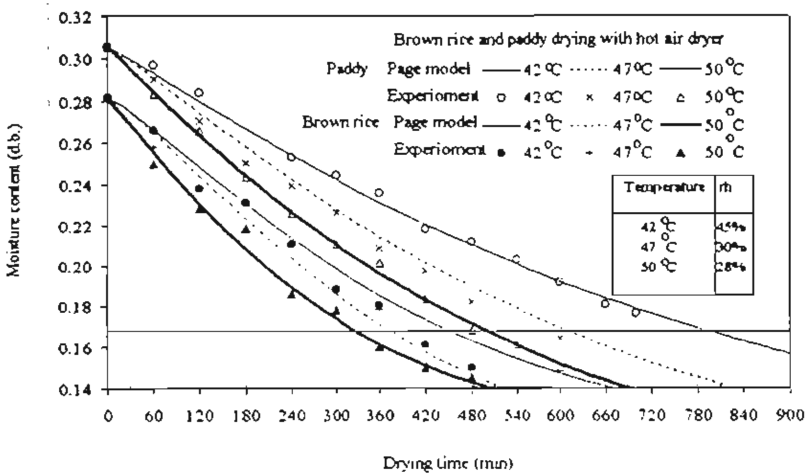

Fig. 5 Comparison between simulated and experimental moisture contents of paddy and brown rice dried by hot air dryer

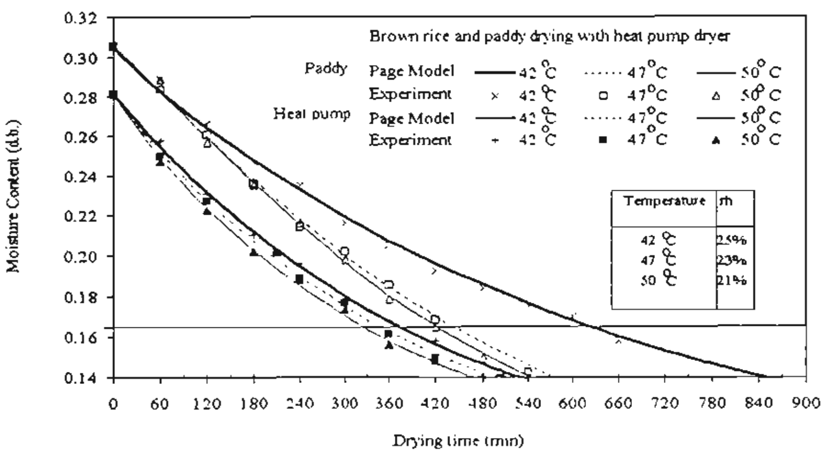

Fig. 6 Comparison between simulated and experimental moisture contents of paddy and brown rice dried by heat pump

samples dried by heat pump and hot air dryers was higher than 43.

Conclusions

From the experimental study on drying of paddy and brown rice using hot air and heat pump dryers, it can be concluded as follows:

Drying Kinetics

1. Drying time for paddy drying is 1.3-1.5 times of that for brown rice drying.

2. Drying rate of paddy and brown rice using heat pump is higher than that of hot air dryer. It was due to lower relative humidity of drying air in the case of heat pump dryer.

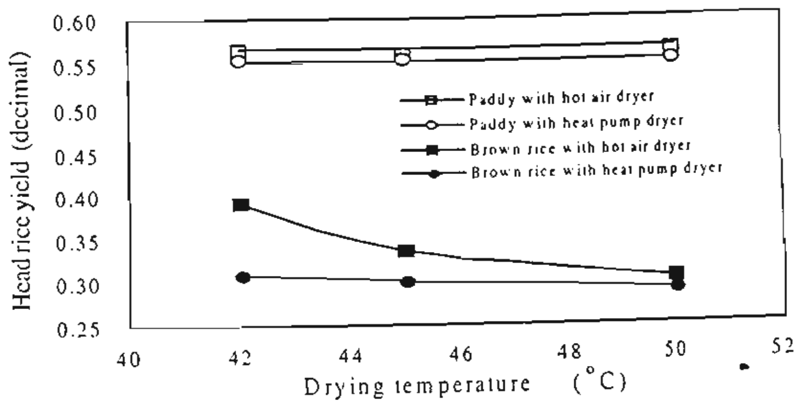

Fig. 7 Effect of drying temperatures on head rice yields for drying paddy and brown rice by heat pump and hot air dryers

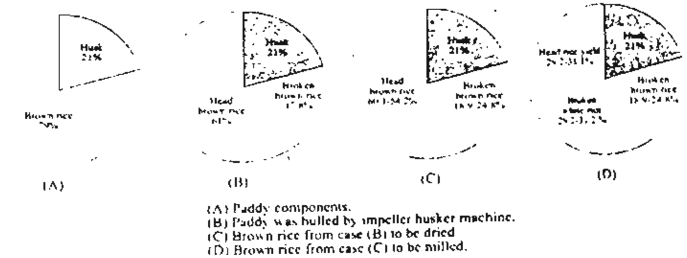

Fig. 8 Change of head rice yield and breakage of brown rice in the stages ofhulling (B), drying (C) and milling (D)

Rice Quality

1. In case of brown rice drying using hot air dryer, the head brown rice yield is higher than when using heat pump.

2. Drying air temperature is the main variable that affects head rice yield, especially in the case of brown rice drying using hot air dryer.

3. In brown rice drying process, the breakage of brown rice was increasing in the following processes: dehusking, drying and milling.

4. The drying of paddy and brown rice using heat pump or hot air dryer in this study yields the value of rice whiteness higher than 43 as measured by Kett-C300 whiteness meter.

Acknowledgements

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Studies on Drying of Paddy and Maize in Bangladesh

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Keywords : paddy, maize, solar drying, computer simulation

Abstract

Drying of paddy and maize in Bangladesh is mainly done by sun drying. Annual loss of grain from harvesting to consumption is estimated to be 10 to 25%. Experimental and simulated studies to address the problems of drying of paddy and maize are presented. Although these enormous studies provided simulation and optimization models as tools for optimal design of solar and mechanical dryers, these dryers are not a competitive alternative to sun drying. The causes of the non-acceptability of the solar and mechanical dryers for drying of grains by target farmers are addressed. Mechanical dryers are advantageous as compared to sun drying for drying of seed and the potentiality of efficient and cost effective mechanical dryers for production and marketing of quality seeds of paddy and maize are discussed.

PADDY is the main cereal grain in Bangladesh and maize ranks third after rice and wheat. The drying of cereal grains in Bangladesh is mainly done by sun drying. Usually rural farmers spread the grains on beaten earth or woven mats and the grains are directly exposed to solar radiation. Although sun drying offers a cheap method, it often results in inferior quality due to its dependence on weather conditions and vulnerability to the attack of insect, pests, microorganisms and dust. Some of the high yielding varieties of paddy are harvested in the wet season and farmers lack facilities to dry the grains to a moisture content that will allow safe storage for at least a week waiting for subsequent sun drying. As a result a significant loss of the harvested paddy in both quantity and quality occurs. Annual loss of grain from harvesting to consumption is estimated to be 10-25%. Appropriate post harvest technology can contribute to reduce post harvest losses.

Some of the high yielding varieties of maize are also harvested in the wet season The major problem that is likely to affect the production of maize is the drying and storage of maize at farm level (Mondal, 1995). At a grain moisture content above 12% and at a high relative humidity (>70%), there is a possibility of insect attack and mould growth and possibility of production of aflatoxin in maize grain (Mondal, 1995). When aflatoxin contaminated grain is used as poultry feed, the birds are infected and the risk of large scale mortality may occur. Recently, due to presence of aflatoxin in poultry feed, thousands of birds were infected and the newly developed poultry industry faced a great challenge for its existence. Hence it is high time for researchers to come forward to develop suitable technology for drying and storage of maize in Bangladesh In order to address drying problem of paddy and maize efforts have been made to develop dryers, drying systems and drying strategies. There has been enough work although there is still a lot of scope for further researches on fluidized bed drying and in store drying. This paper presents grain drying research and problems in Bangladesh.

Drying of Paddy

High solar radiation, decentralized use, low energy demand and high fossil fuel prices favor the use of solar energy for drying (Muhlbauer *et al.* (1993). It is widely recognized that significant reductions in the post harvest losses can be achieved by use of some form of solar dryers. Many experimental and theoretical studies have been conducted to develop solar dryers.

Three different categories of natural convection solar dryers such as (i) cabinet type solar dryer, (ii) mixed mode solar dryer and (iii) AIT type solar dryer were fabricated and tested at Bangladesh Agricultural University, Mymensingh. The AIT

Sukprakam, C., S. Ruay-Aree, G Srzednicki, B. Longstaff, B. McGlasson, A. Hocking, J. Van, S. Graver, A. Wongkobrat and P. Visarathanonth, eds. 2002. Quality management and market access. Proceedings of the 20th ASEAN/2nd APEC Seminar on Postharvest Technology, Lotus Hotel Pang Suan Kaew, Chiang Mai, Thailand, 11-14 September 2001. 540 pp.

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Cover photograph:

1 Paddy (Suphanburi 2) (photo : Rice Research Institute. Bangkok, Thailand)

2-3 Fruits and vegetables in market, Bangkok. (photo : M. Kongchuensin)

4 Fluidised bed dryer (photo : S. Soponronnarit)

Quality Management and Market Access

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Chiang Mai, Thailand

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Simulation of Paddy Yellowing During Deep Bed Drying

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Keywords: drying model, paddy, in-store drying, rice quality

Abstract

The main objective of this work is to study the yellowing of paddy during drying in a bin. The Hunter b unit was used to indicate the degree of yellowness. The experiment is set up at ambient temperature with a fixed bed depth of 1.0 m. Air is forced continuously through the paddy bulk at a specific airflow rate of 0.93 m³/min-m³ paddy. The initial moisture content of paddy was 20.1% wet basis (wb). The desired final moisture content of paddy is about 14% wb. A near-equilibrium drying model developed by Soponronnarit has been modified by including yellowing kinetics of rice during drying. The results show that the drying rate and the whiteness predictions are in good agreement with those obtained in the experiment.

To cover tropical weather conditions, the simulation model included temperatures between 30 - 40°C, relative humidity (RH) of 60 - 90%, paddy bed depths 1.8 - 3.6 m, initial moisture content 18% wet basis and specific air flow rates of 0.35 - 1.0 m³/min-m³ paddy. The simulation results indicate that the degree of yellowness increases with the inlet air temperature and the relative humidity. To maintain the white colour of paddy and not exceed the acceptable limit of dry matter loss (£ 0.5%) it was found that RH should be lower than 70% and airflow rate higher than 0.35 m³/min-m³ of paddy.

FRESHLY harvested paddy contains 18 to 23% moisture expressed on wet basis. The management of high moist paddy during the harvesting period is a serious problem because high humidity air can favour the excessive mould growth. Dry matter loss and heat liberated from grain respiration and biological activities may accelerate rice yellowing. (Soponronnarit and Nathakaranakule, 1990) To avoid quantity losses of paddy and prevent the above problems, moisture content should be reduced by appropriate drying (for examples direct sun drying, shade drying and mechanical drying). In-store paddy drying, which is the known fix-bed drying, is the most common method. This method of paddy drying always yields good quality of milled rice because of its low drying temperature and low air flow rate (Soponronnarit, 1988; Soponronnarit and Chinsakolthanakorn, 1990). To ensure a high head rice yield, the recommended drying temperature should not exceed 50°C (Soponronnarit and Preechakul, 1990). For high germination rate, a drying temperature of less than 43°C was recommended (Preechakul and Soponronnarit, 1986; Soponronnarit, 1987a;1987b) suggested that drying time for in-store drying should not exceed 12 days for paddy at 20% moisture content wet basis and 21 days for paddy of 18% moisture content wet basis in order to maintain a dry matter loss not higher than 0.5%.

Quality index of commercial importance, which is used as important criterion for judging quality of rice and set its price, is the rice yellowing. Many researchers have studied on physical quality either in term of yellowness or whiteness (Quitco, 1982; Gras and Bason, 1989 a ; Soponronnarit *et al.*, 1998; Phillips *et al.*, 1989 ; Yap *et al.*, 1988; Gras and Bason 1989 a) reported that the loss of nutritive value of rice occurred when the rice had an intense yellow colour.

Quitco (1982) observed yellowing of milled rice and concluded that the accumulation of fungal metabolites (*Fusarium* sp., *Aspergillus flavus*) might produce typically the distinctly yellow individual rice kernel while the non-enzymic browning might

cause the overall change in hue. Some micro-organisms, such as: *Curvularia* sp., *Aspergillus terreus* and *A. ochraceus* might produce blackened rice kernels (Quitco, 1982 b). Some researchers (Gras and Bason, 1989 ; Soponronnarit *et al.*, 1998; Phillips *et al.*, 1989; Yap *et al.*, 1988) studied the influence of the water activity, temperature and storage atmosphere on the yellowing of white rice kernels.

Yap *et al.*(1988) studied the effect of physical parameters and concluded that the moisture content, variety and aging affected yellowing of paddy, brown rice and white rice. Grain moisture content was in range of 12-20% wet basis. Drying temperature was fixed at 60°C for 4 days drying time. The results was shown that changes in color as indicated by *L*, *a* and *b* values in terms of Hunter unit system were significant. The Hunter *b* value increased with increase in moisture content, and was the highest value in paddy.

Gras *et al.* (1989) concluded that water activity and temperature intensively affected the degree of yellowing rate and the rate was slightly affected by presence of oxygen (O_2) but not by carbon dioxide (CO_2). Equation for yellowing prediction also was proposed in their works (Gras *et al.*, 1989; Bason *et al.*, 1990 ; Soponronnarit *et al.*, 1998). The equation formulated by Gras *et al.* (1989b) could be used for predicting the yellowing rate in range of 35 to 60°C and water activity of 0.40 to 0.80, which were the same conditions as those described by Bason *et al.*(1990). Soponronnarit *et al.* (1998) studied on the yellowing of rice kernel. Initial moisture content of paddy was about 19.4% wet basis. The 5x3 factorial design was used with two replications and analyses of variance to study the effects of temperature, water activity and their interaction on rate of yellowing. The yellowing was measured as a Hunter *b* value and the whiteness was also measured. The results concluded that the yellowing rate was the zero order kinetic reaction and the equation could be used for predicting the yellowing rate for the range of 35 to 65°C and water activity of 0.80 to 0.95%. Their yellowing equation obtained by the authors was slightly different from the previous works. The statistical analysis showed that temperature, water activity and their interaction significantly influenced the yellowing rate of paddy.

Mathematical Drying Model

Mathematical models for deep layer grain drying can be divided into following 3 models: non-equilibrium model (Brooker *et al.* 1974), near-equilibrium model (Thompson *et al.*,1968); Soponronnarit, 1988 ; Soponronnarit and Chinsakolthanakorn, 1990; Soponronnarit and Nathakaranakule, 1990) and logarithmic model (Hukill, 1947; Barre *et al.*,1971).

The mathematical deep bed paddy drying model uses in this work based on a near-equilibrium model, which has been developed by Soponronnarit, 1988. The main equations of model are as follows:

Energy balance equation for a thin layer

The sum of changes of the internal energy of the control volume of a thin bed and enthalpy of flowing stream is equal to zero. The following equation can be thus written as:

$$c_a T_o + (2502 + c_V T_o) W_o + R c_{pw} \theta_o = c_a T_f + (2502 + c_v T_f) W_f + R c_{pw} T_f \qquad (1)$$

where
c = specific heat capacity, kJ/kg°C
T = air temperature, °C
q_o = grain temperature, °C
W = absolute humidity, kg H_2O/kg dry air
R = ratio of dry grain mass to dry air mass, kg dry matter/kg dry air

With subscripts:
a = dry air; f = after drying
o = before drying; pw = wet grain
v = water vapor

Mass Balance Equation for a Thin Layer

The assumption is that water vapor evaporated from the thin layer is equal to the change of water vapor in flowing stream. The equation of mass balance can thus be written as:

$$W_f - W_o = (M_o - M_f) R \qquad (2)$$

where M = grain moisture content, decimal dry basis

Thin layer drying equation

An empirical thin layer drying equation developed by Agarwal and Singh (1977) is used. It can be written as the following equation:

$$MR = \left(\frac{M - M_{eq}}{M_{in} - M_{eq}} \right) = \exp(-xt^{y}) \quad (3)$$

$$x = 0.02958 - 0.44565RH_0 + 0.1215T_0 \quad (4)$$

$$y = 0.13365 + 1.93653RH_0 - 1.77431RH_0^2 + 0.009468T_0 \quad (5)$$

where RH_0 = relative humidity of air before drying, decimal
M_{in} = initial grain moisture content, decimal dry basis
M_{eq} = equilibrium moisture content, decimal dry basis

Dry matter loss, DML

The dry matter loss of grain is a function of storage time, moisture content and temperature [Soponronnarit, (1993)]. Seib *et al.* (1980) studied the dry matter loss of paddy and predicted its quantity in terms of grain temperature and moisture content. The equation can be written in the following empirical form:

$$DML = 1 - \exp[TERM] \quad (6)$$

in which

$$TERM = a\left(\frac{t}{1000}\right)^{c} \exp[D(1.8\theta - 29)]\exp[E(M_w - 0.14)] \quad (7)$$

where DML = dry matter loss, decimal
t = storage time, h
θ = grain temperature, °C
M_w = grain moisture content, decimal dry basis

For long grain

a, c, d, e = 0.001889, 0.7101, 0.0274 and 31.63, respectively.

Yellowness of rice kernel

The yellowing rate of paddy was investigated in terms of temperature and water activity and an empirical equation for predicting the yellowing rate was developed by Soponronnarit *et al.* (1998) as given by

$$\frac{db}{dt} = k \quad (8)$$

and

$$\ln(k) = 71.87 - 25.32a_w - \frac{25919.13}{T} + \frac{10712.78a_w}{T} \quad (9)$$

where b = yellowness of rice, Hunter *b* unit
t = time, day
k = constant value for the yellowing rate, Hunter *b* unit/day
a_w = water activity, decimal
T = temperature, K

The whiteness of rice (W) was also studied and relationship between the whiteness and yellowness was followed as equation (10)

$$W = 85.1 - 3.36\,b \quad (10)$$

Where W = whiteness of rice, %

Finally, the average moisture content and the average whiteness can be determined by Equation (11) and (12), respectively.

$$\overline{M}_w = \frac{\int_0^L M(x)dx}{\int_0^L dx} \quad (11)$$

$$\overline{W}_w = \frac{\int_0^L W(x)dx}{\int_0^L dx} \quad (12)$$

where

$\overline{M}_w$ = average moisture content of paddy, % wet basis
$\overline{W}_w$ = average whiteness of rice kernel, %
$M(x)$ = moisture content of paddy, % wet basis
$W(x)$ = whiteness of rice in each bed depth, %
dx = bed depth, m

The objective of the present research is to study in-store drying of paddy under ambient hot and humid climates and to investigate the quality of paddy during drying. The yellowing of rice has been investigated during the drying period and the mathematical model developed by Soponronnarit and Nathakaranakule (1990), for predicting the rate of drying and describing the physical quality in term of yellowing has been tested.

Materials and Methods

Materials

Figure 1 shows a deep bed dryer system that comprises a drying bin (1), an electric heating unit (2) and an outlet air duct (3). The experiments of deep bed paddy drying were conducted in an insulated cylindrical bin having a diameter of 0.75 m and a height of 2.75 m. The bed depth of paddy was fixed at 1.0 m. Ambient air was blown through a perforated steel sheet and then into the grain bed. The airflow rate was varied by changing the speed of centrifugal fan with forward curved blades with a butterfly valve (4). The air was forced through the paddy bed from the bottom to the top and the exit air was discharged to the atmosphere at exit duct (3).

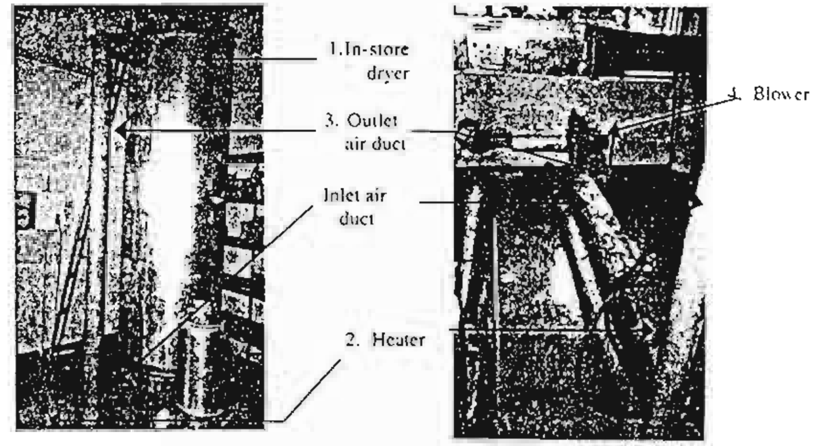

Fig. 1 Schematic diagram of In-store drying system

Methods

Dry paddy (12% wet basis) was rewetted by spraying water, mixed and kept in a cold storage at a temperature of 2°C for 5 days. The moisture content of paddy was determined by standard air oven method at 103°C for 72 hours. The accuracy of electric balance was 0.01 g. The paddy was dried by continuously blowing drying ambient air with a volumetric flow rate of 0.93 m^3/min-m^3 of paddy.

During the experiments, inlet air temperature, moisture content, grain temperature at each bed depth, exit air temperature, head rice yield and whiteness were measured. The grain temperature, dry bulb and wet bulb air temperature were measured by K-type thermocouple, which were continuously recorded by a data logger with an accuracy of ±0.1°C. Air relative humidity was determined from dry and wet bulb temperatures. Air velocity was measured by a hot wire anemometer. Physical quality of paddy in terms of head rice yield, whiteness and yellowness of paddy were determined and compared to the control samples (rewetted paddy with 20% moisture content wet basis subjected shade drying). The methods followed the guidelines of Rice Research Institute, Ministry of Agriculture and Cooperatives, Thailand. The head rice yield was defined as the ratio of mass of head rice obtained from milling to mass of paddy before milling. Relative head rice yield referred to the ratio of head yield obtained from the above-mentioned process to head rice yield obtained from the controlled samples. The yellowness of rice kernel was calculated from the whiteness and indicates in terms of Hunter b unit.

Grain Drying System Program

The mathematical model of Grain Drying System Program (GDS) incorporating the above equations was written in QBASIC language. The grain moisture content and grain temperature at the beginning of the experiment were used as the initial conditions. Temperature and relative humidity of inlet air were the input parameters for calculation in the program. The major assumption was that there exists thermal equilibrium between grain and drying air.

In this GDS, the deep bed grain drying was based on the assumption that the bed was composed of a series of thin layers. Each thin layer was calculated as follows: (Soponronnarit and Nathakaranakule, 1990)

- Equilibrium temperature between inlet air and grain in a thin layer using energy balance equation [Equation (1)] is calculated.
- Relative humidity of the air after thermal equi-

librium is calculated. If relative humidity is higher than 1.0, condensation is simulated by employing an equation similar to Equation

(1) with an assumption that relative humidity after condensation is equal to unity.

- Change in moisture content in a thin layer using thin layer drying equation [Equation (3)].
- Air properties after the calculated change in moisture by using mass balance equation for thin layer drying [Equation (2)] and energy balance equation [Equation (1)].

The above step described the drying stage simulation of a single layer of grain in deep bed dryer. The exhaust drying air condition from the first thin layer would be treated as the input drying air conditions to the next layer and the same procedure for calculations (starting step 2) were made for all thin layers with advancing time step.

The paddy yellowness in each thin layers is calculated during drying time by using the air temperature and air relative humidity, which are in the thermal equilibrium with thin layer of grain kernel, using Equation (8) to Equation (10). The average moisture content and the average whiteness can be calculated by Equation (11) and Equation (12), respectively.

Results and Discussion

Moisture Profiles of Paddy and Energy Consumption

The results are divided into 2 parts. First, the comparison between moisture content during in-store drying of paddy and simulation result is presented. This is followed by the discussion of the simulation model for describing the proper strategy of in-store drying of paddy.

In the first part, results are shown in Figures 2-4. The paddy was dried from initial moisture contents of 20% wet basis to 13.9% wet basis using ambient air. The ambient temperature and the relative humidity throughout the experiment are represented in Figure 2. According to Figure 2, the average air temperature and relative humidity of inlet air was 27.7°C and 75.7% respectively. Figure 2(a) shows the moisture content in each bed depth during the drying period, indicating that the moisture content obtained in the experiment tend to be slightly lower, particularly at the top of the bed, than the moisture contents predicted by the model. Figure 2(b) shows the predicted average moisture contents, which included or not the respiration effect. The simulation including the respiration effect shows the moisture content predictions more accurately than the excluding the respiration effect. Moreover, this respiration effect is the impartial contribution to reduce the moisture content of grain.

Energy consumption reported in this paper includes only the mechanical energy used for driving the fan. Heat loss at the motor was not included in our analysis. Comparison of specific energy consumption between prediction and experiment does not show significant differences: 0.11 MJ/kg of water evaporated obtained from the model vs. 0.09 MJ/kg of water evaporated obtained from experiment. It was found that the energy consumption for evaporating water was relatively low. This is because the value of specific energy consumption, caused by grain respiration effect, corresponding to dry matter loss of 0.9%, is about 1.77 MJ/kg of water evaporated. This energy is used for reducing moisture content of grain during the drying process.

Paddy Quality

An average initial whiteness value of rice is 50.3 and the average final value of whiteness is 48.8 after drying for 936 hours. Comparison between the predicted value of whiteness and the experimental values of whiteness is shown in figures 3(a)-3(c). The experimentally determined rice whiteness values in upper levels are slightly higher than that in higher bed levels. This is because drying rate in the lower bed levels is higher than the higher bed levels due to lower relative humidity of the air. The Figures 3(a)-3(c) show a good agreement between the predicted whiteness and the experimental values.

This result indicates that the continuous drying with ambient air does not have a insignificant effect on the rice color The head rice yield decreases slightly during drying time as shown in Figure 4. There is no obvious explanation of this result so far. More research is needed to be able to understand this phenomenon.

Drying Strategy

To investigate the proper drying using low-temperature air, simulation model has been used at air temperatures between 30 - 40°C, relative humidity (RH) of 60 - 90%, paddy bed depth of 1.8 - 3.6 m, initial moisture content of 18 - 20% wet basis, initial whiteness of 48 and specific air flow rates ranging between 0.35 and 1.0 m³/min-m³ of paddy. The results of simulation are as follows:

Whiteness-relative humidity of ambient air

The relation between whiteness and relative humidity of ambient air is shown in figure 5(a). The

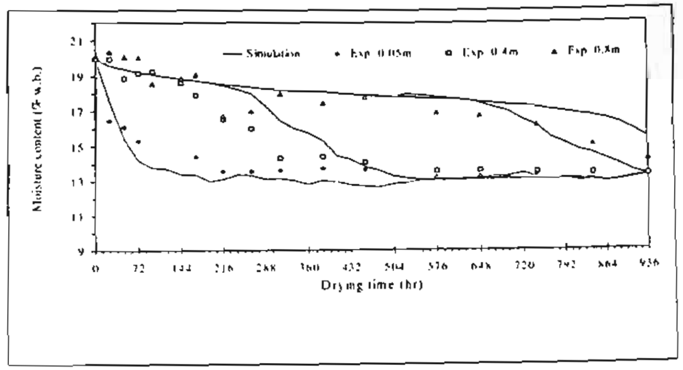

Fig. 2(a) Evolution of mositure content of paddy at different depths: Mi 20% wb; Mf 14% wb ; Air flow rate of .93 m3/min-m3 of paddy

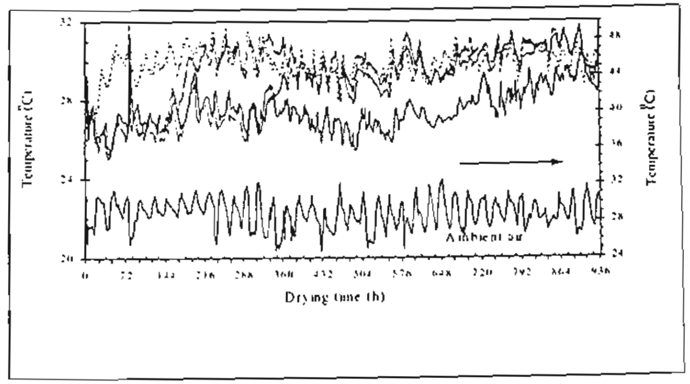

Fig. 2(b) Evolution of temperature profile of paddy at different depths: airflow rate of 0.93 m3/min-m3 of paddy; Mi 20% wet basis; Mf 14% wet basis:Bed depth 1.0 m; Include respiration effect

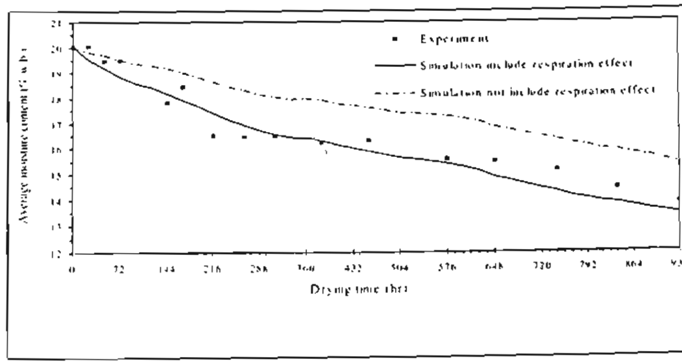

Fig. 2(c) Evolution of average moisture content of paddy : Mi 20% wb : Mf 14% wb : Ambient air flow rate of 0.93 m3/min-m3 of paddy

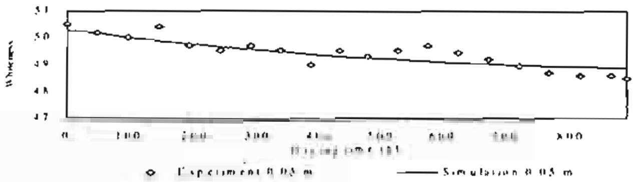

Fig. 3(a) Evolution of whiteness during drying; Initial Whiteness 50.3 : Ambient air ventilation 0.93 m3/min-m3 of paddy; Mi 20% wb; Mf 14% wb

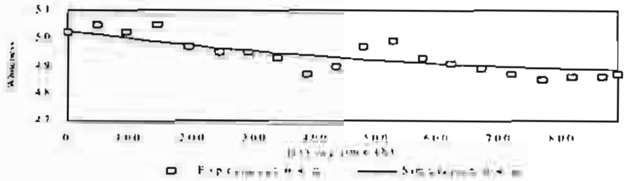

Fig. 3(b) Evolution of whiteness during drying : Initial Whiteness 50.3; Ambient air ventilation 0.93 m3/min-m3 of paddy; Mi 20% wb; Mf 14% wb

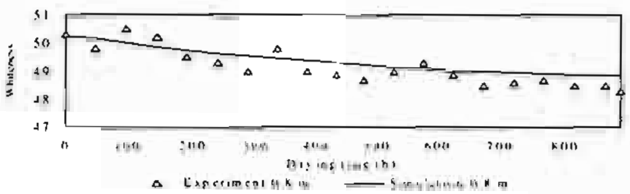

Fig. 3(c) Evolution of whiteness during drying time : Initial Whiteness 50.3 : Ambient air ventilation 0.93 m3/min-m3 of paddy : Mi 20% wb · Mf 14% wb

Fig. 3 Evolution of whiteness of rice at different bed depths during drying

results indicate that at air temperature of 30°C, there is not a significant difference in whiteness within the relative humidities between 60% and 90%. However, at temperature of 35°C and 40°C, the whiteness values show a large change when relative humidity of air inlet is higher than 70%.

Whiteness-airflow rate

The whiteness results show that at the specific air flow rate between 0.5 to 1.0 m^3/min-m^3 of paddy, the whiteness value has changed slower than the specific airflow rate of 0.35 m^3/min-m^3 of paddy as shown in figure 5(b). It appears that the decrease of whiteness value in the region of 2.5-3.6 m bed depth is higher than the decrease of whiteness value in a bed depth of 1.8 m. Therefore at a low specific airflow rate of 0.35 m^3/min-m^3 of paddy in-store drying may cause concerns due to reduction in whiteness value, especially at higher bed depths of paddy.

Based on the results of this simulation, the recommended specific air flow rate should be higher than 0.35 m^3/min-m^3 of paddy. The deep bed paddy drying at the specific airflow rate of 0.5 m^3/min-m^3 of paddy is the most economic drying strategy.

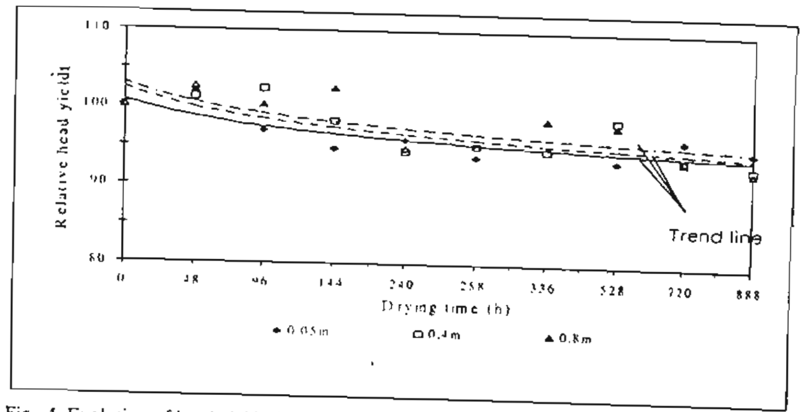

Fig. 4 Evolution of head yield of rice during drying: Mi 20% wet basis; Mf 14% wet basis; Ambient air flow rate of 0.93 m3/min-m3 of paddy

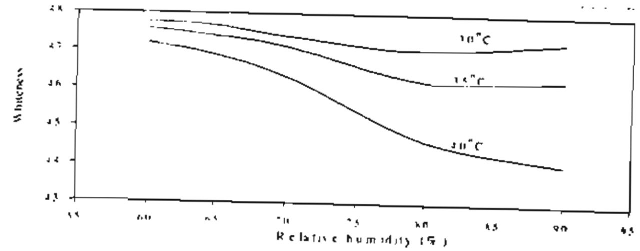

Fig. 5(a) Evolution of whiteness and relative humidity of air during in-store drying of paddy at an airflow rate of 0.5 m3/min-m3 of paddy; Mi = 18% wet basis

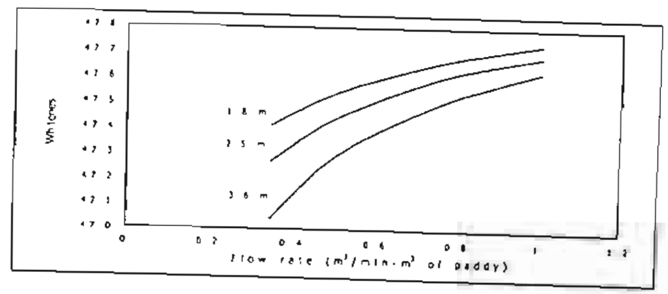

Fig. 5(b) Evolution of whiteness and airflow rate of air during in-store drying; RH 70%; Mi 18% wet basis

Fig. 5 Evolution of whiteness of rice during drying time

Conclusions

1. The 1.0 m deep bed drying of paddy using ambient air has no effect on the yellowing of rice kernels and requires low energy input (0.11 MJ/kg of water evaporated)

2. The modified GDS program including the yellowing model can be used to describe the drying kinetics and rice whiteness in deep bed dryer during the drying process.

3. The drying simulation including the respiration effect predicts the moisture content more precisely than that without the respiration effect.

4. The temperatures between 30°C and 40°C, along with the relative humidity of 70%, is recommended. The specific airflow rate should not be lower than 0.35 $m^3/min \cdot m^3$ of paddy.

Acknowledgements

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1 Paddy (Suphanburi 2) (photo : Rice Research Institute. Bangkok, Thailand)
2-3 Fruits and vegetables in market, Bangkok. (photo : M. Kongchuensin)
4 Fluidised bed dryer (photo : S. Soponronnarit)

Quality Management and Market Access

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Corn Drying by Two-dimensional Spouted Bed Technique

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Keywords: corn, drying kinetics, drying models, spouted bed dryer

Abstract

Changes of physical quality attributes and drying kinetics for corn in a two-dimensional spouted bed dryer (TDSB) with draft plates have been investigated. Three semi-empirical models, Page's, Lewis' and Wang and Singh's, have been used to fit the experimental data. The experimentals have been conducted at a fixed initial moisture content of 38% dry basis (db), inlet air temperatures of 130, 140 and 150°C and hold-ups of corn of 20, 25 and 30 kg. From the experimental results, it appears that the inlet air temperatures and the hold-ups of corn greatly affected the drying rates. The degree of stress crack, breakage and the change of colour of corn depend on the final moisture content. If the moisture content of corn is reduced below 22% db, the stress cracks and the breakage increase significantly. The Lewis' model is the most appropriate for predicting the drying rate.

THE advantages of the two-dimensional spouted bed technique are as follows: (1) It is good for drying heat-sensitive materials. (2) The quality of product after drying is not reduced. (3) The energy consumption is lower in comparison with other types of dryers, and (4) Solid mixing and effective gas-solid contact in the spout region are good.

Kalwar *et al.* (1991) studied drying of soybean, corn and wheat by using the two-dimensional spouted bed dryer (TDSB) with draft plates, in order to evaluate the performance of the dryer and to develop the drying model (Page's equation, 1952), and investigated the influence of dryer geometry and operating parameters on drying rate. It was found that the parameters that most affect drying rate were inlet air temperature and slot width, respectively. Page's equation was found to yield best fit for moisture ratio prediction of experimental data. Kalwar and Raghavan (1993) and Tulasidas *et al.* (1993) studied drying kinetics of shelled corn in a TDSB unit with draft plates. The effects of inlet air temperatures and bed heights on heat and mass transfer in the drying chamber were conducted. It was found that inlet air temperature strongly affected drying rate, i.e. the latter increased with inlet air temperature. Drying rate of shell corn increased with lowering of the bed height.

Considering the past research, it can be concluded that the focus is on hydrodynamics, heat and mass transfers, development of drying models and the effect of drying parameters on drying rate, but not much on the grain quality after drying. The objectives of this research work are to investigate the effect of drying variables on the corn qualities and to develop the drying models.

Materials and Methods

Materials

Drying studies were conducted in a lab-scale two-dimensional spouted bed (TDSB) with draft plates, as shown in Figure 1. The inlet cross-section area was 0.04 x 0.15 m², width of spout (W_s) 8 cm and entrance height (H_E) 12.5 cm. A 24 kW electrical heater was installed at the ambient air inlet and the temperature was controlled by a thermostat. The fan used was a backward-curved blade centrifugal type, driven by a 2.2 kW motor, directly connected to a variable speed controller. Drying air and corn temperatures were measured by K-type thermocouples connected to a data logger with an accuracy of ±1°C. Drying air temperatures were measured at the inlet and outlet of drying chamber, downcomer region at the levels of 20, 40, 60 and 70 cm above the inlet of drying chamber and draft channel at 50 and 120 cm above inlet of drying chamber. A U-tube manometer and a Pitot were used to measure the pressure drops across the bed and drying air velocity, respectively. The corn samples were taken to determine the moisture content and the quality in terms of breakage, stress cracks and colour.

The moisture content of the test corn was raised to about 38% db, which was nearly to the moisture content of freshly harvested corn, by adding a required amount of water. The wet corn then was stored at 4 - 8°C in a cold room for 5 – 7 days with thorough mixing every 12 hours to obtain an uniform moisture distribution within the corn.

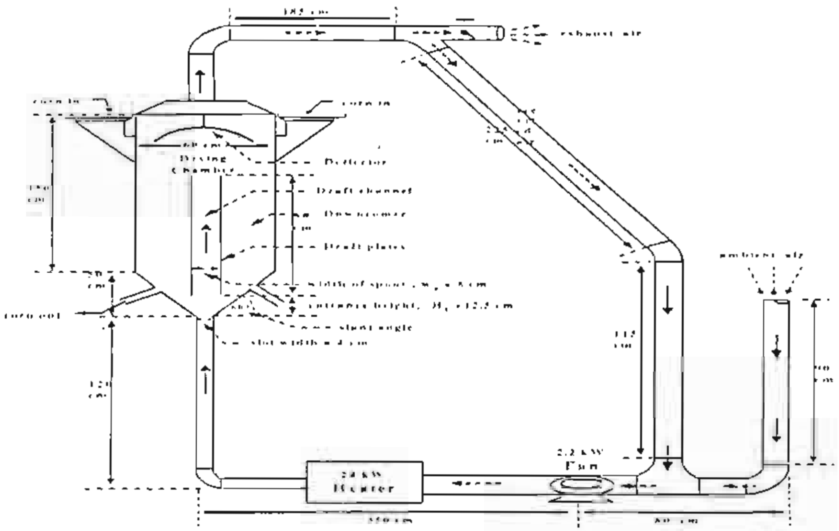

Fig. 1 Diagram of the lab-scale two-dimensional spouted bed with draft plates

Experiments

The Effect of Drying Variables on Corn Quality

In this study, the effects of hold-ups, final moisture contents (M_f) and inlet air temperatures (T_i) on the corn quality were investigated. The experimental conditions were as follows: initial moisture content (M_i) of 38% db, inlet air velocity (V_i) of 17 m/s, inlet air temperatures of 150 and 170°C, and hold-ups of 20 and 30 kg (bed heights of 55 and 75 cm, respectively). The qualities of corn, i.e. breakage, stress crack, and colour were considered.

The Effect of Drying Variables on the Drying Rate

The influence of inlet air temperatures, inlet air velocities and hold-ups were investigated. The experimental conditions were as follows: M_i = 38% db T_i of 130, 140 and 150°C, hold-ups of 20, 25 and 30 kg and inlet air velocities of 17, 19 and 21 m/s.

Development of Drying Models

The semi-empirical drying models, the equations of Lewis (1921), Page (1952), and Wang and Singh (1978) were used. The forms of these equations are as follows:

Lewis' equation	$MR = \exp(-kt)$	(1)
Page's equation	$R = \exp(-kt^n)$	(2)
Wang and Singh's equation	$MR = a\exp(-bt)$	(3)

Where t is drying time, k, n, a, and b are drying parameters, which correlated with inlet air temperature (T_i) and bed height (H_b) in form of linear equation.

Nonlinear technique was used to estimate the numerical values of the model parameters. The fitted models were then evaluated by minimising the sum of square error (R^2) and average squared predicted error (ASPE). Statistica program was used to obtain the suitable value of drying parameters of each equation, in order to find the best fit with experimental data.

Results and Discussion

The Effect of Drying Variables on Corn Quality

Stress Crack of Corn

From the experimental results, it was found that the main factor that affected stress crack of corn was the final moisture content (M_f), as shown in Figure 2. When M_f decreased, stress crack increased. Change of drying air temperature, from 150 to 170°C had little effect on the stress crack of corn, as shown in Figure 3.

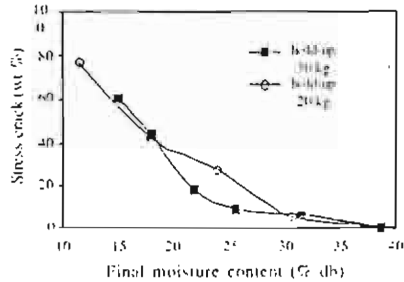

Fig. 2 Effect of final moisture contents and hold-ups on stress crack of corn (T_i = 150°C, V_i = 17 m/s and M_i = 38% db)

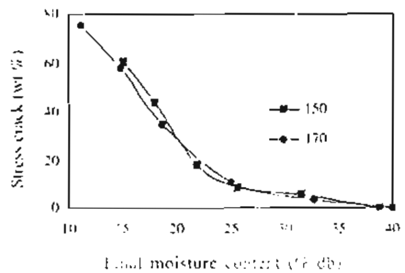

Fig. 3 Relationship between stress crack and M_f at different inlet air temperatures (hold-up 30 kg, V_i 17 m/s and M_i 38% db)

Corn Breakage

Figure 4 shows the effect of final moisture content, M_f and hold-up on corn breakage. It was found that when M_f decreased, percentage of corn breakage increased. When the level of M_f dropped below 22% db the breakage of corn rapidly increased. Figure 5 shows the effect of M_f and T_i on corn breakage. When T_i increased (from 150 to 170°C), corn breakage increased slightly.

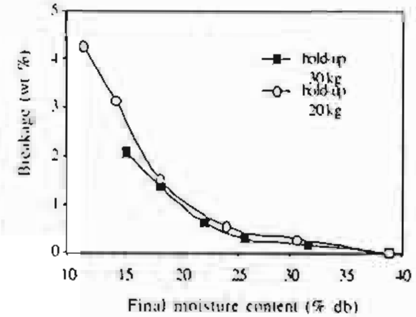

Fig. 4 Relationship between corn breakage and M_f at different hold-ups (T_i 150°C, V_i 17 m/s and M_i 38% db)

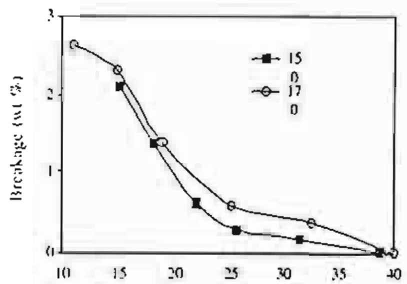

Fig. 5 Relationship between corn breakage and M_f at different inlet air temperatures (hold-up 30 kg, V_i 17 m/s and M_i 38% db)

Corn Colour

From the study of the effect of hold-ups, M_f, and T_i on the colour of corn (whiteness (L), redness (a), and yellowness (b)), it was found that hold-ups had no effect on corn colour. The values of L, a and b varied with M_f, i.e. as M_f decreased L decreased whereas a and b increased. Inlet air temperature, T_i had strong effect on corn colour. The values of a and b increased with T_i, while L decreased, i.e. if T_i

Conclusions

From the experimental study of corn drying using a two-dimensional spouted bed with draft plates and the development of drying models, it can be concluded as follows:

1. The main variable, which affects corn quality after drying, is final moisture content. Drying air temperature and hold-up in the range of study have little effect.

2. Drying air temperature and hold-up are the main variables that affect drying rate.

3. Drying air temperature should not be higher than 170°C, because it results in darker colour of corn kernel. Final moisture content of corn should not be lower than 22% db, because the stress crack and breakage increase.

4. The prediction of corn moisture ratio from using the equations of Page (1952), Lewis (1921) and Wang and Singh (1978) is in good agreement with the experimental results. The Lewis equation is the most appropriate for predicting the drying rate, $MR = \exp(-kt)$ because there is only one parameter k, which varies linearly with the inlet air temperature (T_i) and bed height (H_b).

Acknowledgements

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increased the corn colour would be darker. All of the cases studied, the values of L, a, and b of corn after drying were higher than the standard values. The commercial standard values of which are as follows: value of L should be higher than 47.7, value of a should be lower than 9.7 and value of b should be higher than 23.5.

The Effect of Drying Variables on Drying Rate

The Effect of Drying Air Temperature

Figure 6 shows the relationship between moisture ratio (MR) and drying time at different drying air temperatures (130, 140 and 150°C). It was found that drying rate increased with drying temperature.

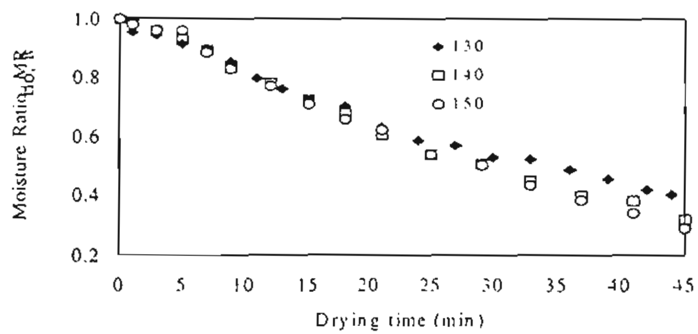

Fig. 6 Evolution of moisture ratio at different inlet air temperatures (hold-up 30 kg, M_i 38% db and V_i 17 m/s)

The Effect of Hold-ups

Figure 7 shows the effect of hold-ups on MR. It was found that if hold-up decreased, MR increased. It was because the residence time of corn in the downcomer region is shorter than the case of higher hold-ups. It resulted in more circulation of corn transported through the draft channel under the same drying time. As a result, the corn was more often contacted with drying air, resulting in faster moisture reduction than the case of higher hold-ups.

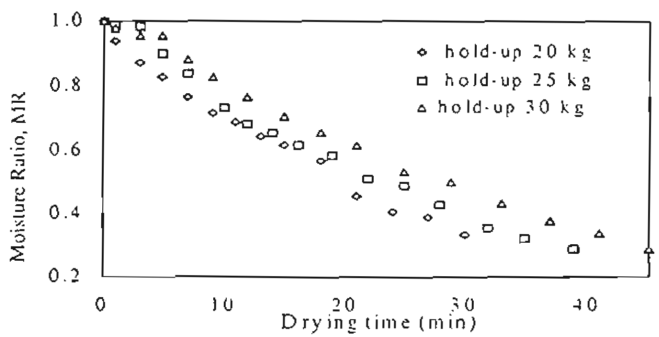

Fig. 7 Evolution of moisture ratio (MR) at different hold-ups. (T_i 150°C, M_i 38% db and V_i 17 m/s)

The Effect of Drying Air Velocity

Figure 8 shows the effect of drying air velocity on moisture ratio. It was found that drying air velocity had little effect on moisture reduction.

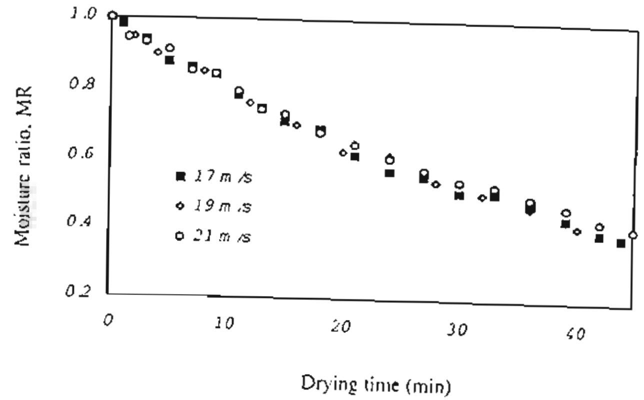

Fig. 8 Relationship between moisture ratio and drying time at different inlet air velocity. (T_i 130°C, Mi 38% db and hold-up 30 kg)

Development of Drying Models

From the development of drying equations (Lewis, 1921 ; Page, 1952 ; Wang and Singh, 1978) it was found that the results of moisture ratio prediction from using these models were in good agreement with the experimental data, as shown in Figure 9. The Lewis model is the most appropriate for predicting the drying rate, MR = exp(-kt), because there is only one parameter k, which varies linearly with inlet air temperature (T_i) and bed height (H_b) as shown below:

$$k = 0.0001835T_i - 0.05007H_b + 0.03490$$
$$(R^2 = 0.9908, ASPE = 4.183\times10^{-4})$$

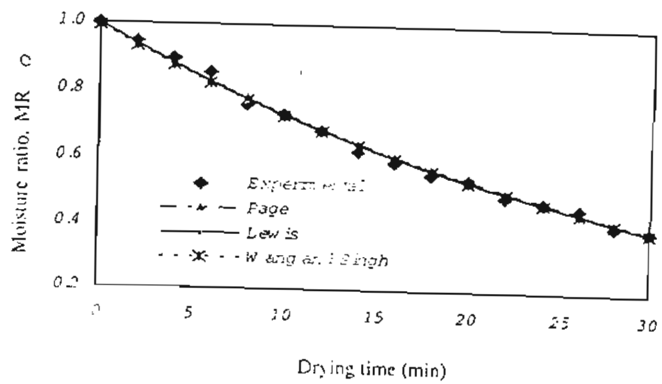

Fig. 9 Comparison between simulated and experimental moisture ratios (T_i 130°C, hold-up 20 kg, V_i 17 m/s and M_i 38% db)

Sukprakarn, C., S. Ruay-Aree, G Srzednicki, B. Longstaff, B. McGlasson, A. Hocking, J. Van, S. Graver, A. Wongkobrat and P. Visarathanonth, eds. 2002. Quality management and market access. Proceedings of the 20th ASEAN/2nd APEC Seminar on Postharvest Technology, Lotus Hotel Pang Suan Kaew, Chiang Mai, Thailand, 11-14 September 2001. 540 pp.

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Cover photograph:

1 Paddy (Suphanburi 2) (photo : Rice Research Institute. Bangkok, Thailand)
2-3 Fruits and vegetables in market, Bangkok. (photo : M. Kongchuensin)
4 Fluidised bed dryer (photo : S. Soponronnarit)

Quality Management and Market Access

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Effect of Moisture and Temperature on Soybean Quality Using a Two-dimensional Spouted Bed Dryer

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Keywords: soybean, protein, urease activity, dryer

Abstract

Proper processing of soybean requires the control of moisture content, temperature and processing time. Adequate moisture during processing facilitates the destruction of the anti-nutritional factors i.e. trypsin inhibitors, saponins and compounds that complex mineral in soybeans. These factors directly affect the growth of animals. To improve the quality of soybeans, the inhibitors are generally inactivated by heat treatment. This paper describes the effect of initial moisture contents and air inlet temperatures on the drying rate and soybean qualities using a batch two-dimensional spouted bed dryer. The experimental conditions were set up as follows: a fixed hold up of 25 kg and air velocity of 15.86 m/s.

The qualities of soybean in terms of cracking, breakage, urease activity and protein have been determined. Urease activity can be measured by detecting pH change, as an indirect test for the trypsin inhibitor. The experimental results show that higher moisture contents and higher temperatures provide faster moisture reduction rates. Soybeans were conditioned to obtain four moisture contents, 14, 22, 28, 32% dry basis (db), and treated with temperatures of 120-150°C. Urease activity and percentages of cracking and breakage were influenced by both factors, the moisture content and the temperature. The increase in the initial moisture levels and the temperatures steeply decrease the urease activity, with the latter showing the more significant effect. In addition, these factors have a detrimental effect on the cracking and breakage. The percentages of cracking and breakage suddenly increase and lie in the range of 1.5-77.4% and of 1.6-7.8%, respectively. In addition to above quality attributes, urease activity levels can be accepted according to the standard levels with values varying between 0.15-0.30, while the protein quality can be maintained as long as temperature is maintained between 140 and 150°C.

SOYBEAN has been long used as a primary protein source in human foods and animal diets. New soy foods have been developed (Lin, 2000; Singh, 2000). Consumption of soy foods is increasing because the cholesterol content is low and the price of soybean protein is lower than that of animal protein. However, raw soybean contain the natural anti-nutritional factors i.e. trypsin inhibitors, haemagglutinins, saponins, and compounds that are the complex minerals. These natural substances affect the growth of animals. Proper processing of soybean requires the control of moisture content, temperature and processing time (Wright, 1981) to inactivate these factors. Adequate moisture during processing facilitates destruction of the anti-nutritional factors in soybeans.

There are three major processes to inactivate the anti-nutritional factors i.e. extrusion, infrared roasting and hot air heat treatment. The first two processes require the high investment and operating costs, while the latter process has the lower investment and operating costs. Several studies have been dedicated to the heating treatment (Stephenson and Tollett, 1959; Renner and Hill, 1960) and the use of extrusion or infrared roasting to improve performance of chicken fed. There are indications that the extruded soybean produced a higher gain weight and growth of animal than the infrared roasted soybean (White *et al.*, 1967; Faber and Zimmerman, 1973).

Recently, fluidisation technique has been used as a means of heat treatment for soybeans to inactivate anti-nutritional factors (Soponronnarit *et al.*, 2001). It was found that it was possible to reduce the level of urease activity, which is an indirect measure of trypsin inhibitor, using 120°C being the minimum required to reduce the urease activity to an acceptable level. The results showed that soybean should not be dried below 23.5% from 33.3% dry basis (db) in order to avoid excessive grain cracking. The optimum conditions for heat treatment corresponded to a temperature of 140°C, bed depth of 18 cm and an air velocity of 2.9 m/s. These conditions resulted in 27% cracking, 1.7% breakage. In addition, Osella *et al.* (1997) studied the fluidised bed technique for drying and inactivation of heat-labile inhibitors in soybeans. As a result, soybean drying and inactivation can be performed in a single step while a high nutritional value can be maintained.

However, the fluidised bed dryer usually provides low heat and mass transfer between solid and gas phases, causing from the bubbling and slugging for such coarse particles (Gishler, 1983). Thus many researches have developed spouted bed technique to improve the performance for drying cereal grains (Mathur and Eptein, 1974; Viswanathan *et al.*, 1986; Massarani, 1987; Pasos *et al.*, 1987; 1989). The aim of the present work was to study not only drying but also reduction in the anti-nutritional factors in soybeans with a two-dimensional spouted bed. In addition, the effects of moisture and temperature on the soybean quality such as percentage of cracking and breakage, urease activity, and protein solubility were also investigated.

Materials and Methods

Soybeans were rewetted to obtain the desired moisture content and kept in a temperature-controlled room between 8°C and 10°C for 5 or 7 days to ensure uniform moisture content throughout the kernels. Then soybeans were treated in a two-dimensional spouted bed dryer (Figure 1) with inlet air temperatures ranging between 120°C and 150°C. The air velocity was 15.9 m/s with a fixed hold-up of 25 kg. The initial moisture contents were 14, 22, 28 and 32% db. Samples were taken at drying times 0, 5, 10, 15, 20, 25, 30 min. The moisture content determination was at a temperature of 103°C in an electrical oven for 72 hr.

The urease activity was determined in each sample, according to AACC standard 22-90 (1976). Experimental data were expressed as pH difference caused by urease converting urea to ammonia. The urease activity value of 0.3 pH difference (maximum) is accepted for a safety level for the soybean meal products. According to AOAC standard (1980), the protein content is defined as percentage of nitrogen multiplied by nitrogen-to-protein factor(6.25). The percentage of nitrogen in soybeans was estimated by Kjeldahl method, using a TKN analyzer.

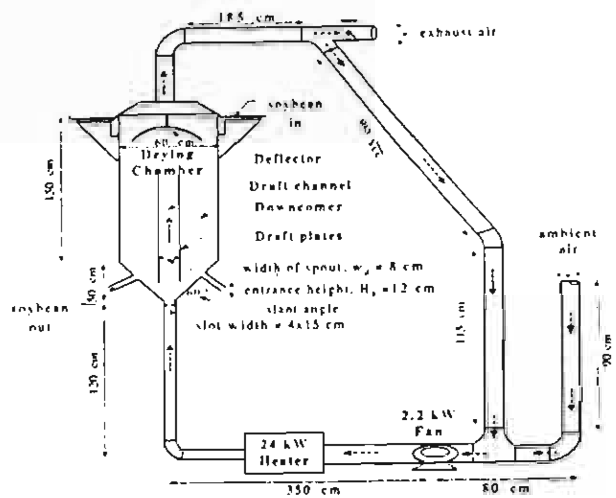

Fig. 1 Schematic diagram of a two-dimensional spouted bed dryer

In addition to above quality attributes, cracking and breakage were inspected visually by identifying the cracked and broken kernels with the help of a fluorescent lamp from 200-gram sample. The percentage of cracking and breakage were expressed by the following equations:

Percentage of cracking=[weight of cracked kernel/weight of sample]x100 (1)
Percentage of cracking=[weight of brocken kernel/weight of sample]x100 (2)

Results and Discussion

Drying Rate

Temperature of grain entering the spout channel as shown in Figures 2(a)-(d) requires different times to reach a steady state temperature within 15-20 min, depending on the inlet air temperatures and soybean initial moisture contents. For example, at 150°C and initial moisture contents of 14, 22, 28 and 32% db, the grain temperatures reach 130, 120, 115 and 112°C, respectively.

At high initial moisture contents (28% and 32% db), grain temperatures are slowly increasing under the same inlet air temperature due to a large amount of heat being used for evaporating water as shown in Figures 2(a)-(b) and 3(a)-(b). At low moisture contents (14% and 22% db), grain temperatures increased considerably while the reduction of moisture content is less significant than in the former case, see Figures 2(c)-(d) and 3(c)-(d). This means that the increase in grain temperature was limited by the presence of water in the kernel.

The reduction of moisture content in the kernel is shown in Figures 3(a)-(d). It was found that drying rates of soybean were increasing with the increase on inlet air temperature and that drying of soybean was occurring in the falling rate period. The final moisture content after 30 minutes of drying varied between 6 and 12% db, depending on the initial moisture content and drying temperature.

Effect of Moisture and Temperature on Urease Activity

Adequate heat treatment facilitates destruction of the anti-nutritional factors in soybean. The test result of urease activity at four different inlet air temperatures (120°C, 130°C, 140°C and 150°C) and at four different moisture contents (14, 22, 28 and 32% db) are shown in Figures 4(a)-(d). Figure 4(b) shows that at an initial moisture content of 28% db, the level of urease decreased to the acceptable level throughout high temperature range considered. At the initial moisture contents higher or lower than 28% db, urease activity are still higher than the desired level along with the temperatures of 120 and 130°C as shown in Figures 4(a), (c) and (d). However, in case of highest initial moisture content (32% db), it requires longer time for heat treatment because at high initial moisture content the large amount of heat is used for evaporating water, so that the grain temperature increased slowly, as shown in Figures 2(a)-(b).

Effect of Moisture and Temperature on Percentages of Cracking and Breakage

The cracks and breakage of soybean drying at high temperatures are displaying a V-shape. These damages are caused by rapid moisture evaporation as reported by Overhults *et al.* (1973) and Soponronnarit *et al.* (2001). The percentages of cracked and broken kernels obtained at different drying temperatures and at different initial moisture contents are shown in Figures 5(a)-(d). The number of cracks and breakage depended strongly on the final moisture contents and inlet air temperatures; they increased with decrease of final moisture content and with increase of inlet air temperature.

For the case of soybeans that were dried from 22.0, 28.0 and 32.0% db to 9.3, 12.3 and 12.4% db at 150°C, the percentage of cracked and broken kernels lies in the range of 58-64% and 3-4%, respectively. But if soybeans were dried from 14.0 to 5.6% db, percentage of cracking and breakage was 14.4 and 2.0%, respectively. This indicated that drying at low initial moisture contents results in smaller numbers of cracked and broken soybeans than that at high initial moisture contents at the same inlet air temperature (120°C-150°C). The cause of larger amounts of stress cracks and breakage was the rapid moisture evaporation at surface of kernel at the higher initial moisture content. On the other hand, at low initial moisture content, evaporation rate of water was very low, therefore, percentages of cracking and breakage decreased.

Effect of Moisture and Temperature on Soybean Protein

In addition to soybean quality attributes mentioned above, the protein content should also be considered. Table 1 shows protein content before and after heat treatment. It appears that the protein content is slightly changed with inlet air temperature and moisture content. Moreover, the soybeans have a brown color when the temperature exceeds 150°C and the initial moisture content is below 14% db.

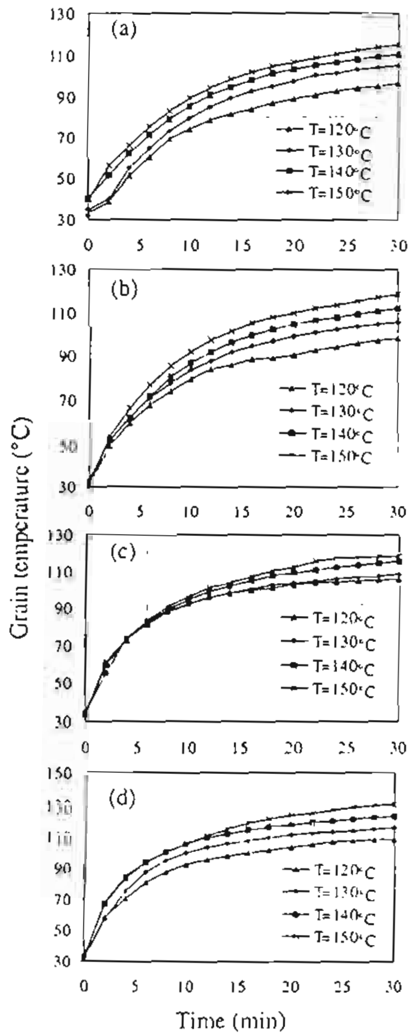

Fig. 2 Temperature of grain entering the spouting channel in function of drying time at initial moisture contents of (a) 32%, (b) 28%, (c) 22% and (d) 14% db

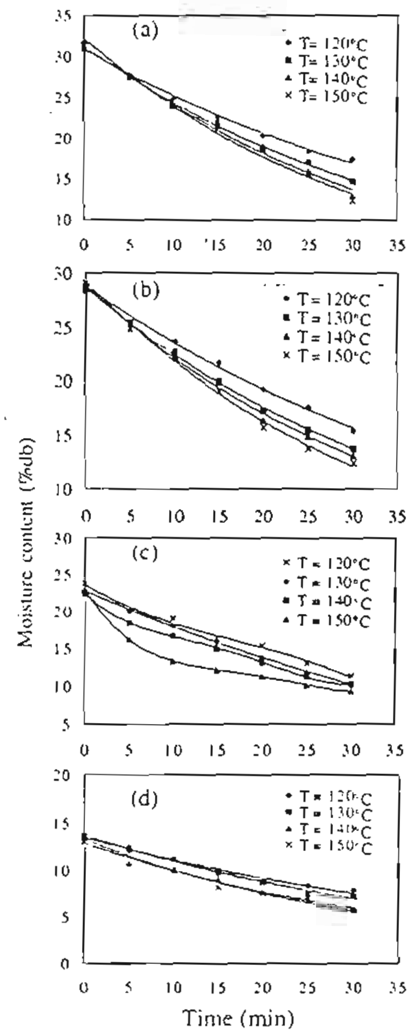

Fig. 3 Moisture content of soybeans in function of drying time at initial moisture contents of (a) 32%, (b) 28%, (c) 22% and (d) 14% db

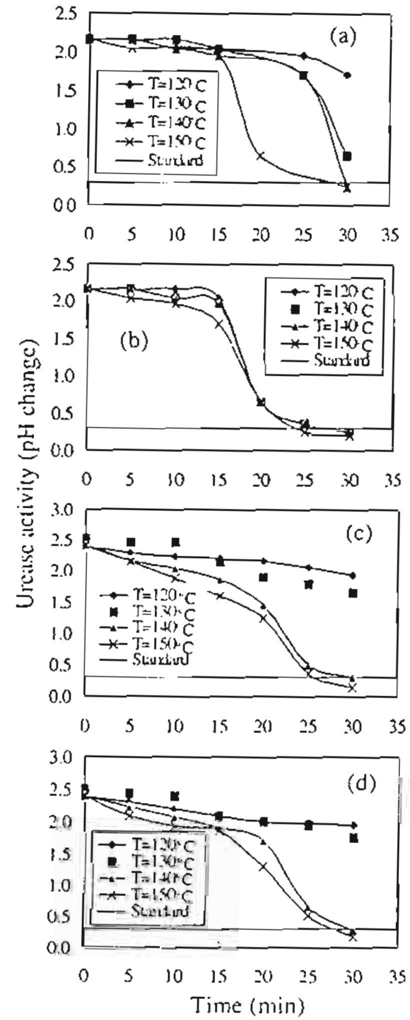

Fig. 4 Urease activity as a function of drying time with initial moisture contents of (a) 32%, (b) 28%, (c) 22% and (d) 14% db

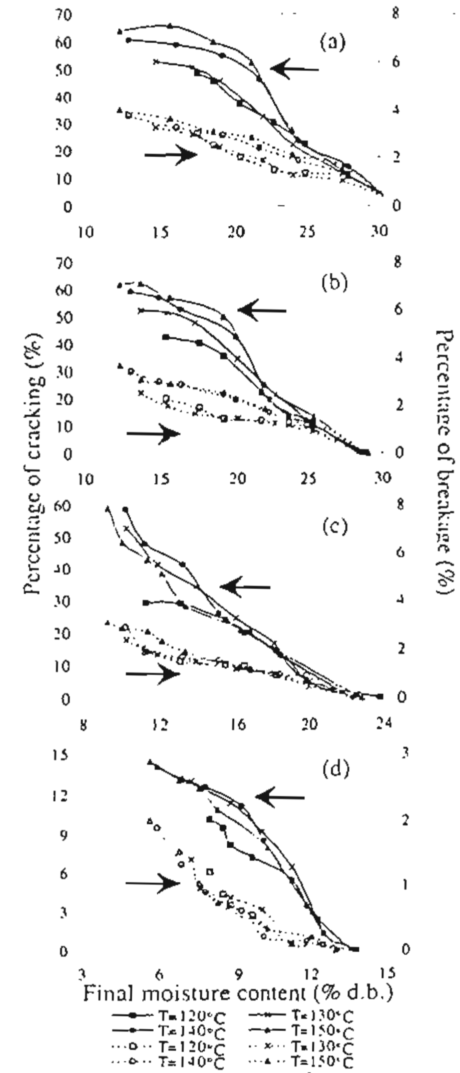

Fig. 5 Percentage of cracking and breakage as a function of final moisture content with initial moisture contents of (a) 32%, (b) 28%, (c) 22% and (d) 14% db

Conclusions

Two-dimensional spouted bed dryer can be used for drying and heat treatment. It can reduce the urease to adequate level and maintain the protein content as long as the drying temperature remains between 140 and 150°C. Under these conditions, moisture content was reduced from 14-32% db to 6-15% db. The degree of cracking and breakage depend strongly on both temperature and final moisture content. To maintain the color of soybeans, the inlet air temperature should be lower than 150°C and the final moisture content should be higher than 6% db.

Acknowledgements

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Table 1 Comparison between protein content in raw and dried soybeans

T_i* (°C)	M_i* (% db)	Protein in raw beans	Protein in dried beans	T_i* (°C)	M_i* (% db)	Protein in raw beans	Protein in dried beans
120	22	40.6	39.0	120	14	43.8	41.8
130	22	43.7	43.4	130	14	42.8	41.3
140	22	42.7	40.7	140	14	43.5	42.2
150	22	40.8	39.8	150	14	42.4	42.3

*Note T_i = inlet air temperature and M_i = initial moisture content

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FLUIDIZED BED PADDY DRYING USING SUPERHEATED STEAM

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ABSTRACT

Fluidized bed drying using superheated steam was used to reduce the moisture content of the product from 45 % dry basis to 16-28 % dry basis. The conditions conducted in this experiment were the initial moisture contents of paddy of 25-45 % dry basis, bed heights of 10, 12.5 and 15 cm, and the temperatures of 150 and 170^{o}C a with constant pressure of 106.1 kPa. The effect of inlet superheated steam temperature on the removal of moisture was much more significant than that of bed height. It was possible to reduce the high moisture content of the paddy down to 18 % dry basis with capable of maintaining the quality of the paddy in terms of head rice yield. Comparing to previous works on fluidized bed drying using hot air, the paddy dried with superheated steam has approximately 30 % higher quality of head yield. It was also found that the initial moisture content had a significant effect on the white belly of rice product.

Key Words and Phrases: Grain; Head rice; Quality; White belly.

INTRODUCTION

Paddy is an important food crop in the world. This cereal is processed into several products, in addition to a staple food. Before having passed through processes, freshly-harvested paddy needs to be dried in order to avoid the quality deterioration by microorganisms and respiration effect.

A drying method which is utilized effectively for essentially high moisture grains, for example, paddy, parboiled rice, soybean and maize, is a fluidisation technique, by which air and solid particles are rigorously mixed. It has been suggested that high moisture paddy should be dried quickly to approximate 23% dry basis (d.b.) and then subjected to ambient air drying in a storage bin until its moisture content is down to 16% d.b. (Soponronnarit and Prachayawarakorn, 1994). Sutherland and Ghaly (1990) pioneered in the intensive investigation on the feasibility of using hot-air fluidised-bed drying technique for paddy.

Their experiments showed that the head rice yield related with the final moisture content: the head rice yield was 58-61% when paddy was dried from 28.2 to 20.5% d.b. but was 15-24% for the final moisture content lower than 20 % d.b. For the transport of moisture in duration of drying by such approach, Tumambing and Driscoll (1991) found that the drying rate of paddy was mainly controlled by internal diffusion.

Drying medium which is used for carrying the evaporated water and fluidising solid particles is hot air and superheated steam. The superheated-steam drying offers important advantages over hot air drying: I) the energy supplied to the dryer can be saved economically by recycling the exhaust steam for the system being operated in a closed loop, II) the energy from the exhaust steam resulting from the evaporation of moisture inside the solids can be recovered and used in the other sections, III) the environmental pollution or the odour emission to atmosphere can be eliminated, IV) oxidation in the superheated steam drying can be prevented due to free oxygen atmosphere, thus improving the product qualities in particular colour, texture and nutritive values (Padua and Juliano, 1974).

General characteristics of the drying process insignificantly change when superheated steam is used instead of hot air. The major differences include: I) the steam condensation at the material surface during the initial of drying period, II) higher drying rate in superheated steam at above inversion temperature, III) no gas film resistance around the solid surface, allowing the enhancement of mass transfer rate.

The use of high steam temperature over its saturation point may cause a serious problem for thermally sensitive food materials, such as browning reaction, discolouration and protein denature. In some cases, however, it provides beneficially for changing the textural property, for example, shrimp drying with superheated steam presented a lower degree of shrinkage than that using hot air (Prachayawarakorn et al., 2002).

The purposes of this paper are to investigate the drying characteristics of paddy in superheated-steam fluidised-bed dryer and to determine the qualities in terms of head rice yield, whiteness and white belly.

MATERIALS AND METHODS

A batch superheated-steam fluidised-bed dryer is schematically illustrated in Figure 1. It was consisted of five main components: a cylindrical chamber with an inner diameter of 15 cm and a height of 100 cm, a 13.5 kW electrical heater for converting saturated-steam to superheated-steam, a backward-curved blade centrifugal fan driven by a 2.2 kW motor, a reverse flow cyclone and a small boiler with a 31 kg/h capacity of generating steam. Superheated-steam temperature was controlled by a PID controller with an accuracy of ± 1°C. Before using steam for drying, hot air was used for warming up the system until the temperature in every part reached the desired level. Then, the steam was replaced accordingly. The steam generator was generated the saturated-steam at 106 kPa (absolute pressure) with the corresponding temperature of 100°C. When the saturated steam was flowed through the electrical heater, the additional heat was supplied to raise the steam temperature up to the desired level. It was subsequently flowed through the fluidised-bed dryer. After that, the small dust particles and the immature grains being suspended in the exhaust steam were collected at the cyclone. Finally, all quantity of cleaned exhaust steam was reused again.

In preparing the moisture content, the paddy was rewetted to a desired moisture content and then kept in a cool room at the temperature of 3-5^{o}C for 5-7 days to ensure uniform moisture content throughout the kernels. The experimental conditions were set up as follows: initial moisture contents of 25-45% d.b., bed depths of 10-15 cm, superheated steam temperatures of 150-170^{o}C, a fixed superficial velocity of 3.1 m/s. Temperatures at different positions were measured by Chromel-Alumel thermocouples (Type K) connected to a data logger with an accuracy of ± 1^{o}C. After drying, paddy kernels were slowly cooled down to ambient temperature and kept in a polypropylene bag. Then, they were gently ventilated with an ambient airflow rate until their moisture content was reached 16 % d.b.. Finally, a 300 g sample was kept in a seal plastic bag for 2 weeks before testing head rice yield, whiteness and white belly.

The moisture content of paddy was determined by an electrical air oven at a temperature 103^{o}C for 72 h. Paddy qualities in terms of head rice yield and whiteness were determined quantitatively and compared to the reference sample (paddy dried by the ambient air). The methods were followed by the guideline of the Ministry of Agriculture and Cooperatives, Thailand. Head rice is defined as milled rice having kernel length at least three-fourths of its original length. The head rice yield was defined as the mass of white rice that remains as head rice after complete milling divided by the mass of paddy sample.

From the experiments, the head rice yield of fresh paddy samples obtained for each time had a relative difference and it might thus be difficult to compare the paddy quality obtained from different drying conditions. To make a clear comparison, the head rice quality was therefore represented as a relative head rice yield. The relative head rice yield is defined as the ratio of head rice obtained from artificial drying to that from the natural air drying.

In addition to the head rice yield, the other two qualities of paddy, translucence, which was directly measured by whiteness, and white belly were also examined. Characteristic of opaque white spot occurred at paddy kernel may be widely divided into the white belly and the chalky grain. The white belly arises from the incompletely or partially gelatinised paddy, but the chalky grain has its own characteristic depending upon the genotype of paddy, so there still exists in the grain in spite of the complete gelatinisation. The white rice samples were measured the colour by using a Kett digital whiteness meter (Model C-300). Before measuring the colour of sample, the whiteness meter must be calibrated with a white coloured reference, presenting a standard value of 86.3. Throughout this work, the colour of sample was represented in terms of the relative whiteness which was defined as the whiteness of the sample from the artificial drying divided by that from the natural drying.

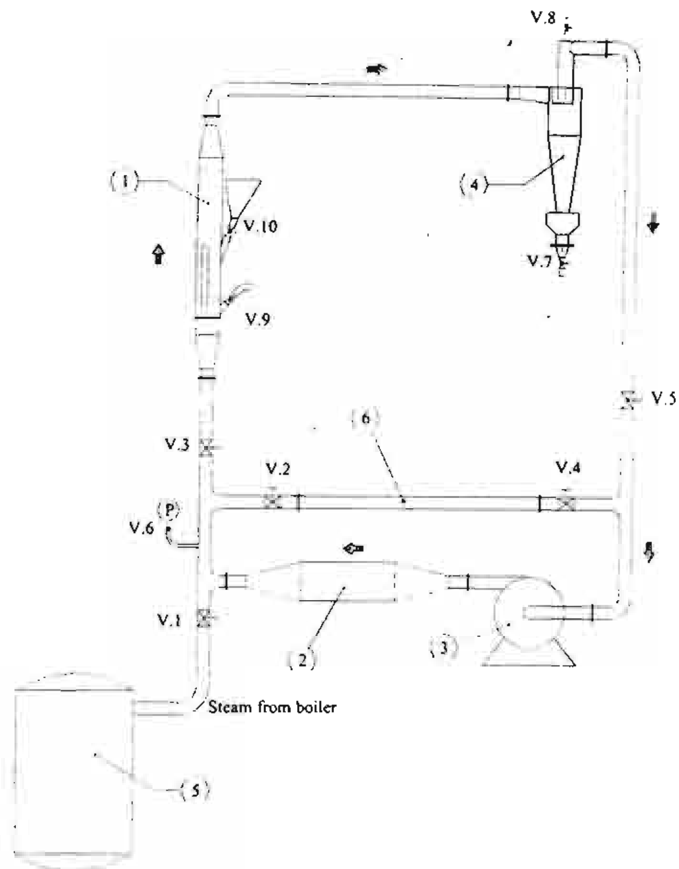

Figure 1 A schematic diagram of superheated-steam fluidized bed dryer: 1) fluidized bed dryer, 2) heater, 3)fan, 4) cyclone, 5) boiler and 6) bypass line

RESULTS AND DISCUSSION

DRYING BEHAVIOUR

Figure 2 shows the behaviour of paddy kernels dried in the superheated steam at different temperatures and bed heights. In the first half a minute, the paddy kernels adsorb a small amount of the condensed water and thus, their temperature rapidly increases to the saturation point corresponding to 100°C. As can be seen in this figure, the samples can gain evenly the water content although the operating parameters such as temperature and bed depth are changed. Such results are dissimilar to the work reported by Tang and Cenkowski (2000), who studied the potato drying in a batch tray dryer using superheated steam. In their work, the initial gain in moisture content varied with the temperature; the samples could gain more moisture content with lower steam temperature. A possible reason for this contradiction can be explained that using high steam velocity in the present work (> 3 m/s for the fluidised bed) leads to the combination of high heat and mass transfer rates accordingly. Thus, the large amount of condensed water existing between kernels evaporates rapidly, instead of diffusing it into the grains. From Figure 2, the initial gains in moisture content for samples at different conditions are approximately 0.02 d.b.

As seen in figure 2, the total drying time for obtaining the given moisture content decreases with the increase in steam temperature, as expected. This is in consistence with the fundamental drying theory, which explains that higher heat flux is transferred to the bed of paddy with higher temperature. Besides the effect of temperature, the bed depth or, in the other words, the total surface area of grains in the bed is another factor that reflects the amount of water evaporation rate from the grains; thicker grain bed depths provide the relatively lower moisture reduction rates for a single gain, thereby allowing the longer drying time. This is because the heat supply is rather small, along with the poorer heat convection. As previously shown in Figure 2, it clearly demonstrated that the temperature was relatively more prevalent contribution, comparing to the bed depth effect.

Figure 3 represents the comparative drying characteristics of paddy in superheated-steam and hot air. After passing through the condensation stage, the moisture content reduces exponentially with drying time, indicating that the main resistance to moisture movement is in the interior. In this moisture reduction step, the drying curve is very similar to that found in the hot air drying, but the total drying time for steam is relatively shorter in spite of the existence of condensation period. The faster moisture reduction is due to the higher heat transfer rate in the superheated-steam at this temperature.

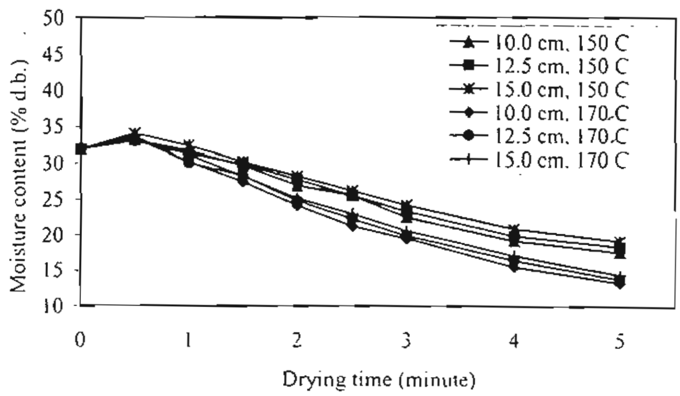

Figure 2 Evolution of moisture content of paddy at different bed heights and inlet superheated steam temperatures

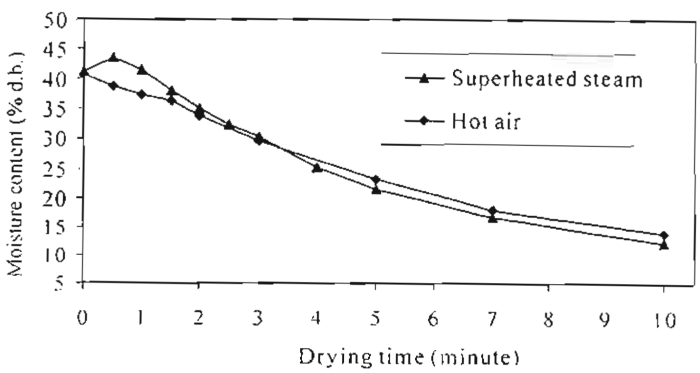

Figure 3 Comparison of drying rates of paddy dried under superheated steam and hot air drying (Temperature = $150^{o}C$, Bed height = 10 cm and velocity = 3.1m/s)

HEAD RICE YIELD

The behaviour of the head rice change in the superheated-steam fluidised bed dryer at different drying conditions is shown in Figure 4. The reference head rice yields of samples vary in a narrow range between 39 and 42%, indicating the uniformity of paddy quality obtained from the fields and the sound quality according to these values. When the paddy was subjected to be dried with steam, the results are clearly evident that the head rice yield from the samples can be maintained or even better than that from the reference samples, with the values being in a wide range of 100 and 180% depending upon the final moisture content. At the final moisture content above 18% d.b., the relative head rice yield is rather constant, showing the values between 160 and 180%. After that, the head rice yield rapidly decreases. The higher head rice yield when compared to the reference one is due to the effect of partial gelatinisation occurring in the paddy grain. To confirm our explanation, we quantitatively determined the white belly

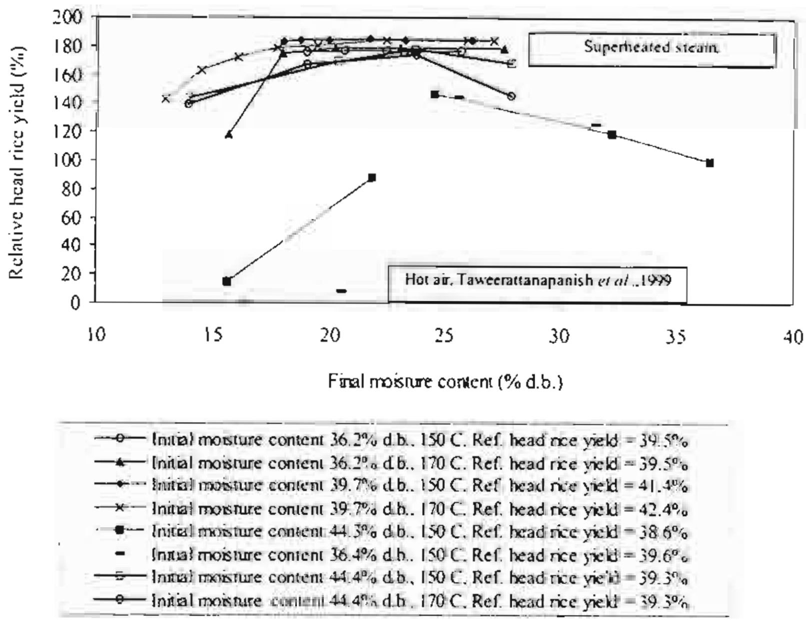

Figure 4 Relationship between relative head rice yield and final moisture contentduring drying in hot air and superheated steam

occurred, as will be shown in Figure 5. In gelatinisation steps, when high moist paddy is heated up and grain temperature reaches the temperature being between 65 and 70°C, its starch cell will swell and loss birefringent property. This causes the protein decomposition and then it will penetrate into the void spaces amongst the starch granules, resulting in reduction of fissures within the grain kernels (Ranghavendra Rao and Juliano, 1970). Consequently, the paddy dried by superheated steam becomes rigid and tough, and can resist to milling, as a result. That is the reason why the head rice yield of paddy dried in the steam is higher than that of reference.

However, the drop of head rice after 18% d.b. may be caused by the prevalent contribution of the tension near the surface and the compression at the centre of kernel, leading to fissure development although some extents of fractures and void space on the grain surface disappeared at the early drying period due to swelling of starch granules.

Comparing to the Taweerattanapanish's work (1999) which was performed with hot air dying, the head rice for samples dried by superheated steam is significantly higher in amount and predominantly more stable in a wider range of final moisture contents. This is because the transfer of heat is very rapid through the steam condensation and then the condition for taking place the gelatinisation is more full fill. However, the completed gelatinisation requires the sufficient amounts of gelatinisation time, water and heat. From the observation, we found that the paddy was not completely gelatinised, according to the detection of white belly.

For the hot air drying, evaporation of water around the grain surface occurs at the wet-bulb temperature and the moisture removal is very fast at initial drying period without condensation, as previously shown in Figure 3, so that the drying goes on with yielding the lower degree of gelatinisation as compared to superheated steam one. The resulting head rice yield becomes lower. As dictated in Figure 4, the level of head rice for hot air samples at 150 and 170°C increases, unlikely to superheated steam ones, when the moisture content is laid down from 44 to 25% d.b., with the highest value of 140% at 25% d.b.

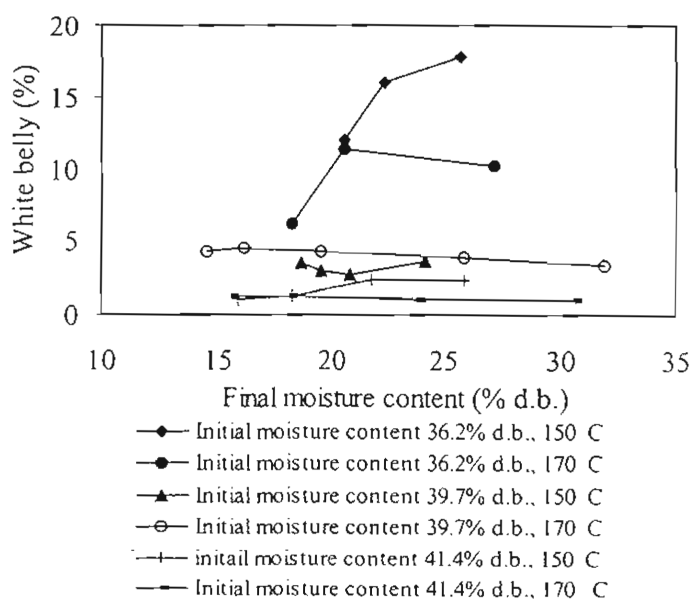

Figure 5 Relationship between percentage rice white belly and final moisture content of paddy at different initial moisture content and temperature

RICE WHITENESS

The change of the colour of samples from the steam temperatures of 150 and 170°C and the initial moisture contents of 36 and 44% d.b. is exhibited in Figure 6. The relative rice whiteness curves at the first 3 minutes of total drying times steeply changes from the original relative value of 100% and afterwards they appears to be slight alternations with the final moisture contents. Such a colour change characteristic for the steam drying takes a more serious effect as compared to the hot air drying(Taweerattanapanish et al., 1999) as depicted in Figure 6, showing the noticeably lower value of the relative rice whiteness for the steam. The main cause of the rapid change in the colour is partly due to the steam condensation onto the paddy surface. The resulting bran covered around kernel is dissolved and then absorbed by the endosperm. To approve our explanation, we checked the quantity of bran after milling the brown rice, with a measured value of 5% which was lower than that from the reference sample (10%).

The temperature used for drying is also an important factor influencing the degree of whiteness; the higher temperature causes the lower value of whiteness. The illustration of this effect can be seen in the case of moisture content 36.2% d.b. and temperatures 150 and 170°C, showing a relative value of 55 at 150°C and of 50 at 170°C for the final moisture content of 23-24% d.b.

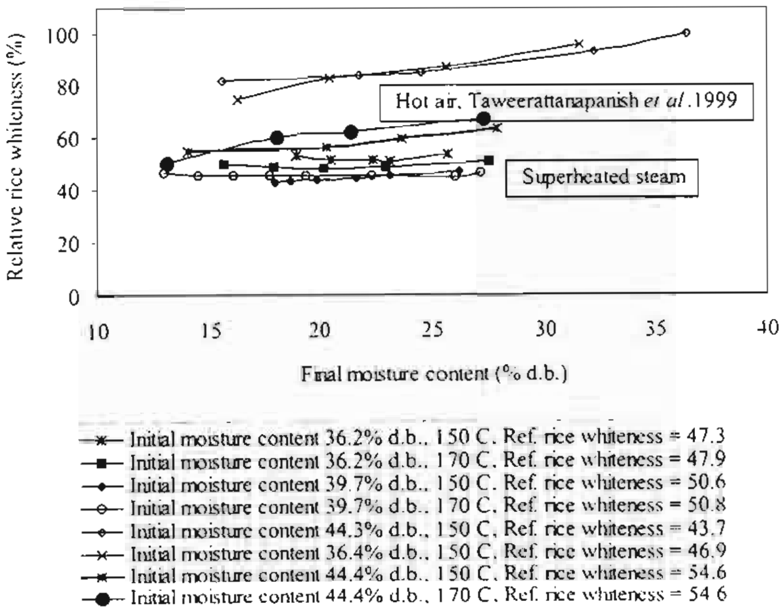

Figure 6 Relationship between relative rice whiteness and final moisture content during drying in hot air and superheated steam

WHITE BELLY

White belly in rice kernel is an indication of gelatinization as previously explained. The individual head rice kernel after milling was graded manually to check the white belly. Kernel obtained from drying which has the opaque white area higher than 50% of its total area is selected to be the white belly category. The white bellies found in the experiments were frequently occurred at the central area of kernel and the area near the endosperm. The percentage of white belly shown in Figure 6 was calculated by the number of white belly kernels divided by the total number of head rice kernels. It is evident that the amount of white belly depends strongly on the initial moisture contents, but it is weakly dependent on the steam temperature. The degree of white belly is significantly lower with higher initial moisture contents. For example, the amount of white belly at 150°C is 10 for the initial moisture content of 36.3% d.b. whilst it is lower than 5, 2% for the initial moisture content of 39.7, 41.4% d.b., respectively. The lower quantity of white belly may imply the higher degree of gelatinisation. In commercial practice, the white belly of less than 1.5% indicates the premium quality of parboiled rice, which means almost completely gelatinized.

CONCLUSIONS

In the first half minute of drying paddy with superheated steam using fluidised bed approach, a small amount of moisture content is slightly gained from the steam condensation onto the surface and the gain in moisture content is rather independent to the steam temperature. The main moisture transport inside a single paddy kernel is controlled by the internal diffusion.

In superheated steam drying, more stable head rice yield in a wider range of final moisture content, together with higher head rice yields, when compared to those from the hot air one, is accomplished whilst rice whiteness apparently darkens. In addition to such qualities, the degree of white belly decreases with increase in the initial moisture content, providing relatively higher head rice yield. To maintain good head rice yield, it recommends that high moist paddy should not be dried to be lower than 18% d.b.

ACKNOWLEDGEMENTS

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EXPERIMENTS ON IN-STORE PADDY DRYING UNDER TROPICAL CLIMATE : SIMULATION AND PRODUCT QUALITY

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ABSTRACT

The main objective of this work is to study the rice whiteness and paddy qualities of rice in terms of hardness, stickiness, cohesiveness and germination of rice. The prediction results of moisture content and whiteness of rice are compared to the experiment results using a near-equilibrium drying model, which is modified by including whiteness kinetics of rice kernel. The long grain rice (Suphanburi1 high amylose *indica* variety), which consists of amylose content of 27%, is used for all experiments. The experiments are set up at the average ambient temperature of 30±4°C, average relative humidity of 76±8% with a fixed bed depth of 1.0 m. Specific air flow rate of 0.65 and 0.93 m^3/min-m^3 of paddy are forced continuously through the paddy bulk at an initial moisture content of 18.5% and 20.1% wet basis, respectively. The desired final moisture content of paddy is about 13.3±0.6% wet basis. The results show that drying rate and the whiteness predictions are in good agreement to those from the experiments The in-store drying using ambient air condition does not produce notable effect on the rice whiteness, head rice yield and the percentage of paddy germination. However, the hardness, stickiness and cohesiveness of rice are significant different.

Keywords: Drying model, Grain, In-store drying, Rice quality

INTRODUCTION

Freshly harvested paddy may contain the water around 18 to 23% wet basis. The management of highly moist paddy during the harvesting period is a serious problem because high humidity condition can encourage the excessive mould growth and the high respiration rate from grain. Consequently, dry matter is lost and heat liberated from respiration and biological activities may accelerate rice yellowing [Soponronnarit and Nathakaranakule, (1990)]. To obtain high quantity of paddy and prevent all the above problems, moisture content should be reduced and gentle drying is an essential technique for this purpose. The in-store paddy drying, which is well known as a fix-bed drying, is the most common method. This drying technique always yields a good quality of milled rice because of low drying temperature and low specific air flow rate [Soponronnarit, (1988); Soponronnarit and Chinsakolthanakorn, (1990)].

To ensure a high head rice yield and a high germination rate of rice, the recommended drying temperature should not exceed 43°C [Soponronnarit and Preechakul, (1990)]. Soponronnarit, (1987a and 1987b) suggested that drying time for in-store paddy drying should not be longer than 12 and 21 days for the moisture content at 20% and 18% wet basis respectively, to be not higher than 0.5%.

Quality index, which is used for considering quality of rice, is the head rice yield and the rice yellowing. Many researchers have studied on physical quality either in term of yellowness or whiteness [Quitco, (1982); Gras and Bason, (1989); Soponronnarit *et al.* (1998)]. Gras and Bason, (1989) reported that the loss in the nutritive value of rice was occurred when the rice had an intense yellow.

Quitco, (1982) observed yellowing of milled rice and concluded that the accumulation of fungal metabolites (*Fusarium sp. Aspergillus flavous*) might be expected to produce typically the distinctly yellowed individual rice kernel while the non-enzymic browning reaction might cause the overall change in hue. Some microorganisms, such as *Curvularia sp., Aspergillus terreus* and *A.ochraceus*, might be expected to produce the black rice kernels. Some researchers [Gras and Bason, (1989); Soponronnarit *et al.* (1998)] studied on the influence of the water activity, temperature and storage atmosphere on the yellowing of white rice kernels. Gras *et al.* (1989) summarized that the water activity and temperature intensively affected the degree of yellowing rate and the rate was slightly affected by the presence of oxygen (O_2) but not by the carbon dioxide (CO_2). Soponronnarit *et al.* (1998) studied on the yellowing of rice kernel. In their work, initial moisture content of paddy was about 19.4% wet basis. The results indicated that the yellowing kinetics were the zero order and the equation used for yellowing rate was in the range of 35°C to 65°C and water activity of 0.80 to 0.95%.

In the present work, the quality of paddy during drying under hot and humid weather is investigated. The yellowing of rice, paste viscosity, hardness, stickiness and cohesiveness of rice (Texture analysis) are considered. A mathematical model developed by Soponronnarit and Nathakaranakule, (1990) for predicting the moisture content and the yellowness is also presented.

MATHEMATICAL DRYING MODEL

Mathematical models for deep layer grain drying can be divided into 3 models as follows: non-equilibrium model [Brooker *et al.* (1974)], near-equilibrium model [Soponronnarit, (1988)] and logarithmic model [Hukill, (1947)]. The near equilibrium model developed by Soponronnarit, (1988) was represented in this work. The main equations of the model are as follows:

(a) Energy balance equation for a thin layer

The sum of changes of the internal energy within a control volume of a thin bed and the enthalpy of flowing stream is equal to zero. The following equation can thus be written as

$$c_a T_o + (2502 + c_v T_o) W_o + R c_{pw} \theta_o = c_a T_f + (2502 + c_v T_f) W_f + R c_{pw} T_f \tag{1}$$

Where c = specific heat capacity, kJ/kg-°C T = air temperature, °C

θ_o = grain temperature, °C W = absolute humidity, kg H_2O/kg dry air

R = ratio of dry grain mass to dry air mass, kg dry matter/kg dry air

With subscripts:

a = dry air
o = before drying
v = water vapor

f = after drying
pw = wet grain

(b) Mass balance equation for a thin layer

The assumption is that water vapor evaporated from the thin layer is equal to the change of water vapor in flowing stream. The equation of mass balance can thus be written as

$$W_f - W_o = (M_o - M_f)\,R \tag{2}$$

Where M = grain moisture content, decimal dry basis

(c) Thin layer drying equation

An empirical thin layer drying equation developed by Agrawal and Singh, (1977) was used. It can be written by,

$$MR = \left(\frac{M - M_{eq}}{M_{in} - M_{eq}}\right) = \exp(-xt^{y}) \tag{3}$$

$$x = 0.02958 - 0.44565\,RH_o + 0.1215T_o \tag{4}$$

$$y = 0.13365 + 1.93653\,RH_o - 1.77431\,RH_o^2 + 0.009468\,T_o \tag{5}$$

Where RH_o = relative humidity of air before drying, decimal
M_{in} = initial grain moisture content, decimal dry basis
M_{eq} = equilibrium moisture content, decimal dry basis

(d) Dry matter loss(DML)

Seib *et al.* (1980) studied experimentally the dry matter loss of paddy and predicted its quantity in terms of grain temperature and moisture content. The equation can be written in the following empirical form:

$$DML = 1 - \exp[TERM] \tag{6}$$

In which

$$TERM = a\left(\frac{t}{1000}\right)^{C} \exp[D(1.8\theta - 28)]\exp[(E(M_w - 0.14)] \tag{7}$$

Where DML= dry matter loss, decimal t = storage time, h
θ= grain temperature, °C M_w = grain moisture content, decimal dry basis

For long grain

a,c,d,e= 0.001889, 0.7101, 0.0274 and 31.63, respectively.

(e) Yellowness of rice kernel

The yellowing rate of paddy depended on temperature and water activity and an empirical equation for predicting the degree of yellowness was proposed by Soponronnarit *et al.* (1998) as given by

$$\frac{db}{dt} = k \tag{8}$$

And $$\ln k = 71.87 - 25.32a_w - \frac{25919.13}{T} + \frac{10712.78a_w}{T} \tag{9}$$

Where b = yellowness of rice, Hunter *b* unit t = time, day
k = constant value for the yellowing rate, Hunter *b* unit/day

a_w = water activity, decimal   T = temperature, K

The relationship between the whiteness and yellowness can be expressed by

$$W = 85.1 - 3.36\,b \tag{10}$$

Where W = whiteness of rice

The average moisture content and the average whiteness throughout the bed height can be determined by Equations (11) and (12) respectively.

$$\overline{M}_{av} = \frac{\int_0^L M(x)dx}{\int_0^L dx} \quad (11) \qquad \text{And} \qquad \overline{W}_{av} = \frac{\int_0^L W(x)dx}{\int_0^L dx} \tag{12}$$

Where $\overline{M}_{av}$ = average moisture content of paddy, % wet basis

$\overline{W}_{av}$ = average whiteness of rice kernel, %

M(x) = moisture content of paddy, % wet basis

W(x) = whiteness of rice in each bed depth, %

x = bed depth, m

L = total bed depth, m

MATERIALS AND METHODS

MATERIALS

FIGURE 1 shows a deep bed dryer which was comprised of a drying bin (Point 1), an electric heating unit (Point 2) and an outlet air duct (Point 3). The experiments of deep bed paddy drying were conducted in an insulated cylindrical bin having a diameter of 0.75 m and a height of 2.75 m. The bed depth of paddy was fixed at 1.0 m. Ambient air was blown through a perforated steel sheet and then into the grain bed. Specific airflow rate was varied by controlling the speed of forward curved blade centrifugal fan and butterfly valve. The air was flowed through the paddy bed from the bottom to the top of paddy bed and the outlet air was then delivered to the atmosphere.

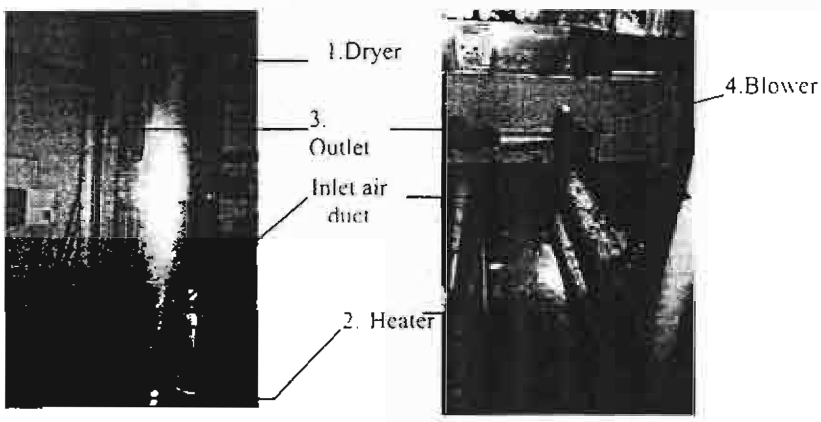


Figure 1 Schematic diagram of in-store drying system

METHODS

Dry paddy (Suphanburi 1, high amylose *indica* variety, moisture content of 12% wet basis) was rewetted by spraying water and then mixed and kept in a cold storage at the temperature of 4-8°C for 7 days. The desired initial moisture content for the experiments are 20.1% wet basis for 1st experiment and 18.5% wet basis for the 2nd experiment. The moisture content of paddy was determined by the standard air oven method at 103°C for 72 hours. The paddy was dried continuously under drying ambient air condition with a volumetric flow rate of 0.93 and 0.65 m^3/min-m^3 of paddy for the experiment no.1 and the experiment no.2, respectively. During the experiments, inlet air, moisture content, grain temperature, outlet air, head rice yield, and whiteness were recorded. The grain temperatures, dry bulb and wet bulb temperatures were measured by K-type thermocouple, which were continuously monitored by a Yogokawa data logger with an accuracy of ± 0.1°C. Air relative humidity was determined from dry and wet bulb temperatures. Air velocity was measured by a hot wire anemometer. Product qualities of paddy in terms of head rice yield, whiteness, yellowness, viscosity and texture properties and germination of paddy were determined and compared to the control samples (The rewetted paddy was dried by ambient air ventilation in a thin layer dryer). The viscosity properties of rice samples were determined using an Rapid Visco Analyzer[RVA](Newport Scientific Ltd.) and texture analysis was determined in terms of hardness, stickiness and cohesiveness of rice using Texture analyzer.

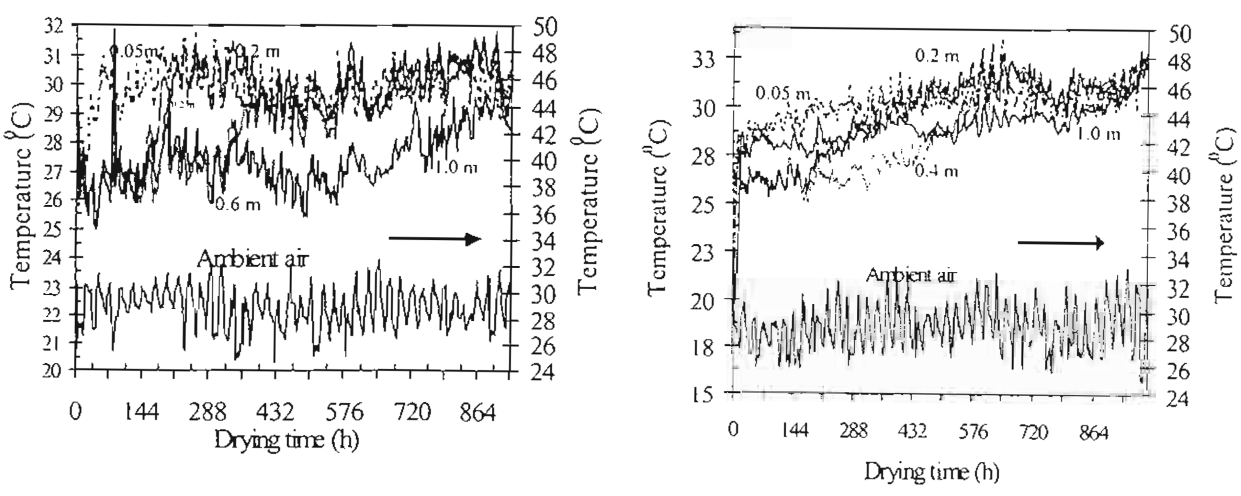
The methods were followed the guidelines of Rice Research Institute, Ministry of Agriculture and Agricultural Cooperative, Thailand. The head rice yield was defined as the ratio of mass of head rice obtained from milling to mass of paddy before milling. Relative head rice yield referred to the ratio of head yield obtained from the above-mentioned process to head rice yield obtained from the controlled samples. The yellowness of rice kernel was calculated from the whiteness and presented in terms of Hunter *b* unit.

RESULTS AND DISCUSSION

MOISTURE PROFILE AND ENERGY CONSUMPTION

The results are divided into 2 parts. Firstly, the comparison between moisture content of paddy and simulation results is presented. Lastly, the product qualities of rice will be discussed.

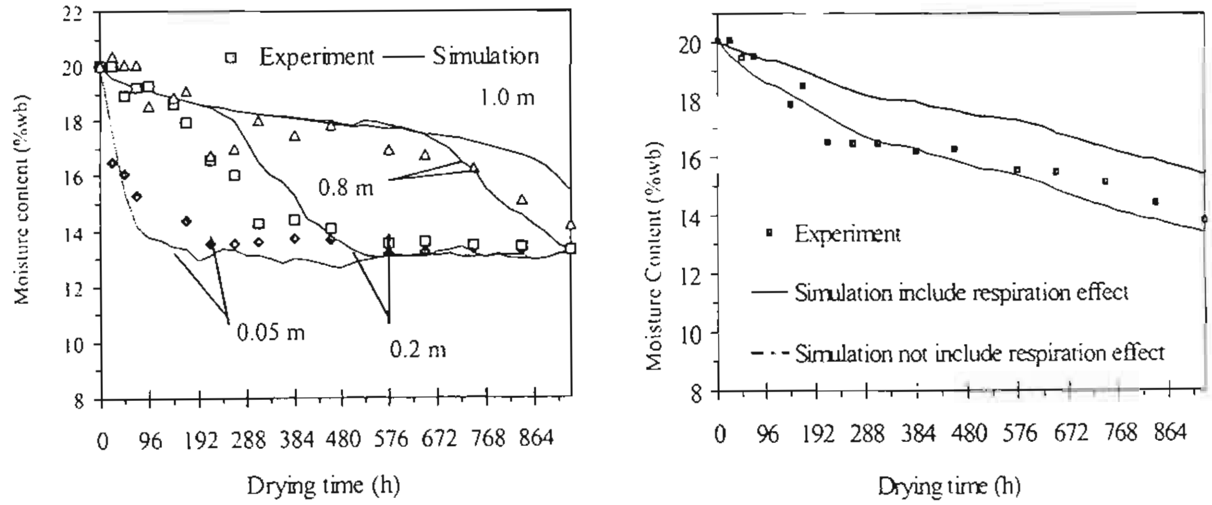
FIGURE 2 illustrated the evolution of temperature profile during drying periods in each bed height. FIGURE 2 showed that temperature profile at bed height, where the paddy was dried, was close to the ambient air.



2(a) Experiment no.1 (0.93 m^3/min-m^3 of paddy) 2(b) Experiment no.2 (0.65 m^3/min-m^3 of paddy)

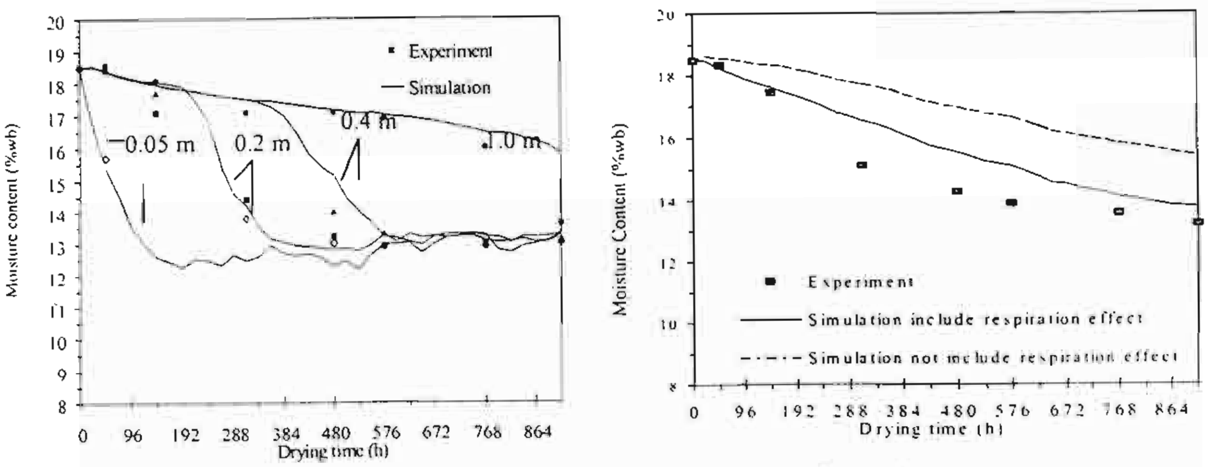
Figure 2. The evolution of temperature profile during drying

The paddy was dried from the initial moisture contents of 18.5% and 20.1% wet basis to 14±1% wet basis. FIGURE 3 illustrates the moisture profile of both experimental results and prediction results. FIGURES 3(a) and 3(c) show the moisture content in each bed depth throughout drying time for the specific flow rate of 0.93 m^3/min-m^3 of paddy (The experiment no.1) and 0.65 m^3/min-m^3 of paddy (The experiment no.2), respectively. The results show that the predicted moisture content tends to be slightly different from the experiment value, particularly at higher bed height which shows the moisture content prediction from the model higher than that from the experiments. FIGURES 3(b) and 3(d) intend to show the average moisture content prediction, which is included and excluded respiration effect for the calculation. The simulation with including the respiration effect shows the moisture content predictions more accurately than the excluded one. In addition, the respiration effect is more pronounced to moisture reduction in particularly at low airflow rate as shown in FIGURE 3(d), comparing to FIGURE 3(b).



Experiment no.1 (M_{in} 20.1% w.b.: M_f 14% w.b. : Ambient air flow rate 0.93 m^3/min-m^3 of paddy)

3(a) Evolution of moisture content during drying 3(b) Evolution of average moisture content during drying



Experiment no.2 (M_{in} 18.5% w.b.: M_f 13.3% w.b. : Ambient air flow rate 0.65 m^3/min-m^3 of paddy) :

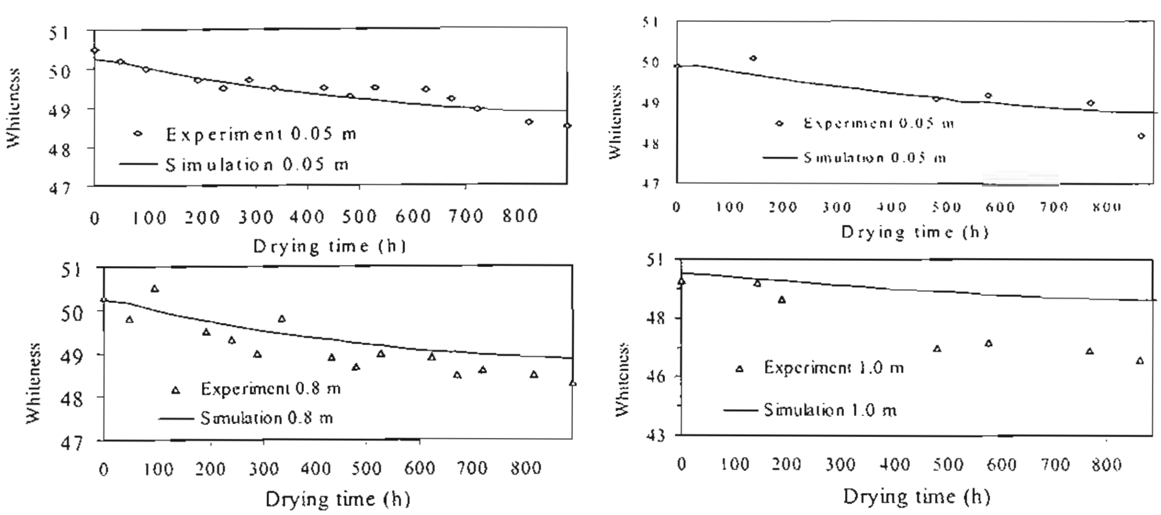
3(c) Evolution of moisture content during drying 3(d) Evolution of average moisture content during drying

Figure 3. Evolution of moisture content profile and average moisture profile during drying

Energy consumption reported in this work covers only the mechanical energy used for driving the fan and heat loss at the motor was not included in the analysis. Comparison of specific energy consumption between prediction and experiment is not significantly different. The energy consumption of both experiments were in range of 0.97-2.11 MJ/kg of water evaporated which is obtained from the prediction values while the energy consumption of 0.09-0.11 MJ/kg of water evaporated is obtained from the experiments. Due to grain respiration effect, energy liberation corresponding to dry matter loss of 0.8-0.9% for both experiments, were about 0.8-2.0 MJ/kg of water evaporated. These amounts were used for evaporating the water. These mean the energy from respiration effect is the impartial contribution to reduce the moisture content of grain.

PADDY QUALITY

In experiment no.1, an average initial whiteness value of rice is 50.3 and the average final value of whiteness was 48.8 after the paddy was dried for 936 hours. For experiment no.2, an average initial rice whiteness is 49.8 and the average final value of rice whiteness was 49 for the bed depth of 0.05m.(bottom level) and 0.4 m.(middle level) after drying for 912 hours. The results were illustrated in FIGURE 4.



4(a) Experiment no.1 (0.93 m^3/min-m^3 of paddy) 4(b) Experiment no.2 (0.65 m^3/min-m^3 of paddy)

Figure 4. The evolution of whiteness of rice during drying period

These values were good agreement between prediction values and experimental values while the paddy at high bed depth of 1.0m (top) was infected by fungi so the rice samples get more yellowing and damage so that its prediction becomes relatively lower is. The result showed that an experimentally determined rice whiteness values at the higher levels was slightly higher than these at lower bed levels as shown in FIGURE 4(a) and 4(b). This was because the drying rate at the lower bed height was higher than that at the higher bed height.

The average initial head rice yield of the experiments was about 50 and the value of relative head rice yield after drying was between 0.92-0.98. For the experiments, the germination of paddy was in range of 92.5-94.5% and 93-95% for control rice and after drying paddy, respectively. The results showed that they were insignificant different. These results could be concluded that in-store drying by ambient air ventilation was not affected the head rice yield and the germination.