ScienceAsia 25 (1999) : 51-56

Fluidised-Bed Paddy Drying

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Received 25 Jan 1999

ABSTRACT The research and development of fluidised-bed paddy drying in Thailand is described in this paper, starting with an experimental batch dryer and culminating with a commercial continuous-flow dryer. A mathematical model of the fluidised-bed paddy drying system is derived. Fluidised-bed paddy dryer is now fully commercialized in several countries. The potential is great, especially for high moisture grain. Energy consumption is relatively low while paddy quality is maintained. In addition, a significant spin-off is that head rice yield can be increased under proper drying conditions.

KEYWORDS: dehydration, fluidisation, grain.

INTRODUCTION

It has been suggested that high moisture paddy should be dried quickly to approximately 23% moisture content (dry basis)* then subjected to ambient air drying in storage.[1,2] Following two-stage drying, cost and product quality appear to be optimised. During the first stage, fluidised-bed 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 overdried 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.

Sutherland and Ghaly[3] were probably the first research group who investigated 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[4] 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.

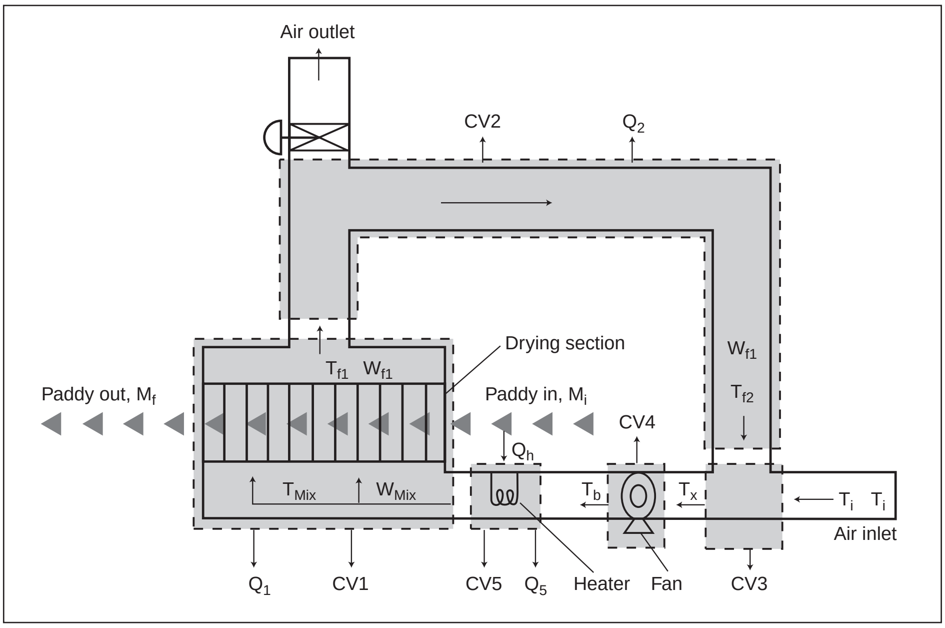

Fig 1. Control volumes of continuous cross-flow fluidised-bed drying system: ◀ grain flow; ← airflow; T, temperature; W, humidity ratio; M, grain moisture content; Q, heat; CV, control volume

* Unless otherwise stated, the moisture contents (mc) quoted in this paper are dry basis.

Research and development work on fluidised-bed drying of grain were reviewed and conducted both experimental and simulation studies on batch fluidised-bed paddy drying.[5] A cross-flow, fluidised-bed paddy dryer with a capacity of 200 kg/hour (Fig 1) was developed.[6] 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.[7,8] The prototype is shown diagrammatically in Fig 2. 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. The 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 following mixing with ambient air and reheating to the desired temperature. The 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 which 0.35 was primary energy from electricity (electrical energy multiplied by 2.6) and 1.79 was primary energy in terms of heat.

As a result of the success of the prototype, commercial fluidised-bed paddy dryers with capacities of 5 and 10 t/hour as shown in Fig 3 are now available. More than 90 units have been sold since the beginning of 1995. The fluidised-bed dryer is mainly 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. Commercial cyclonic rice husk furnace is now available. Operation of commercial fluidised-bed paddy dryer is similar to the prototype except that a small portion of exhaust air is vented to the atmosphere after being cleaned by the cyclone.

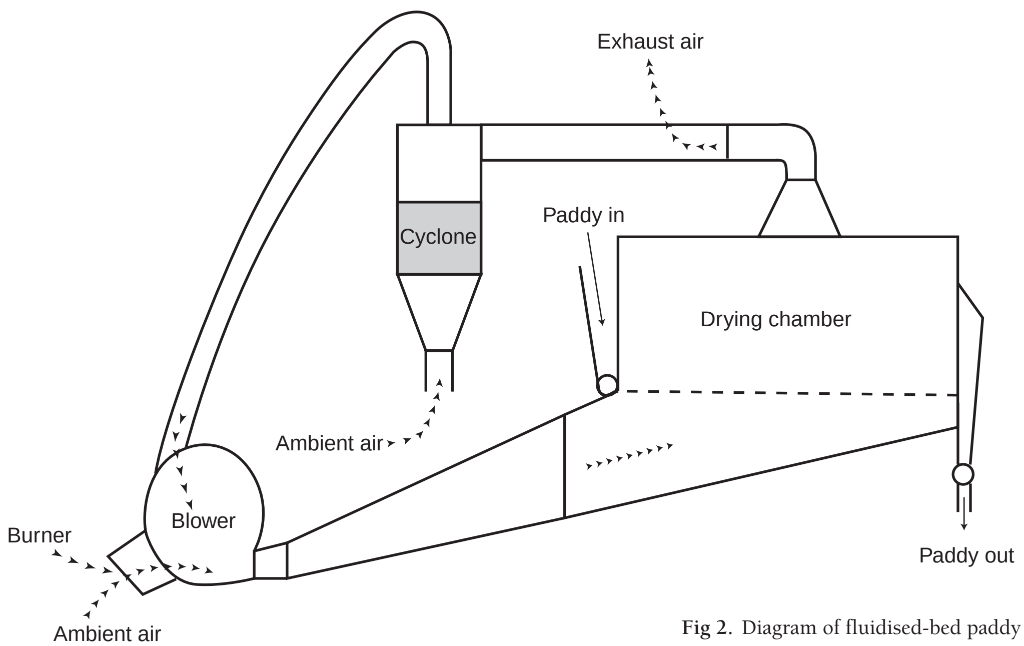

Fig 2. Diagram of fluidised-bed paddy dryer.

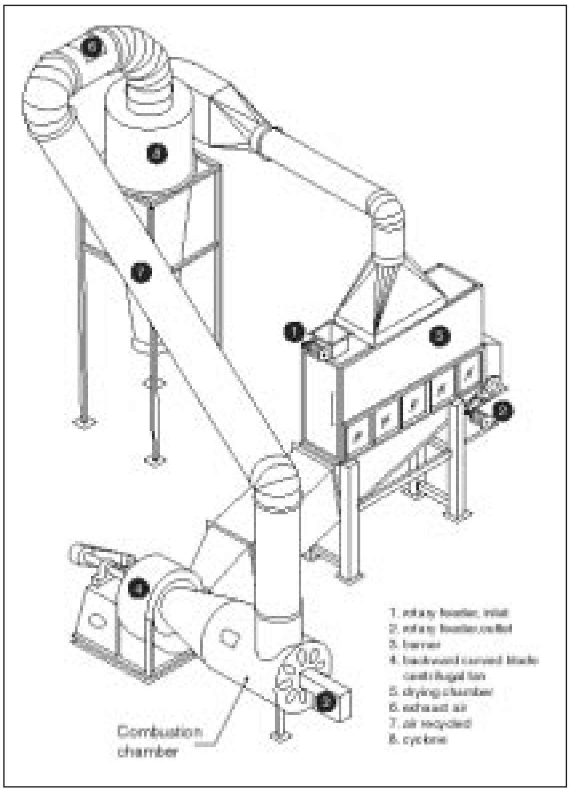

Fig 3. Commercial fluidised-bed paddy dryer.

The objective of this paper is to describe the development of fluidised-bed paddy drying, including the mathematical model used. Important experimental results from both laboratory-scale and commercial dryers will be presented.

Development of Mathematical Model

It was assumed that there was thermal equilibrium between drying air and product, and that the air and grain flow were plug type. The model is similar to that previously presented.[5] Fig 1 shows control volumes (CVs) for the derivation of energy and mass equations based on fundamental physical laws.

1. Equation of mean residence time

The empirical equation of mean residence time of paddy developed by Sripawatakul[9] was used. It is written as follows:

$$\tau = hu/F \qquad (1)$$

where τ = mean residence time, second (s)
hu = hold up, kg
F = feed rate, kg/s

and $hu = [\{-0.0095000 + 0.59870\,F - (0.00020000 + 0.17360\,F)\,V\} + \{1.1728 - 0.082300\,V + (2.2093 - 0.15050\,V)\,F\}\,h]\,\rho_p A$

where A = paddy bed area, m^2
V = air velocity, m/s
ρ_p = average product density, kg/m^3
h = weir height, m

It is valid for weir heights in the range 0.04 - 0.10 m, air velocities in the range 1.7 - 2.3 m/s, and paddy feed rates in the range 0.025 - 0.058 kg/s. For a rough calculation, hu is approximately equal to $hA\rho_p$.

Dividing the paddy bulk into n layers, changes in moisture content of paddy, temperature, and the humidity ratio of air were calculated for each layer. The following basic equations were employed.

2. Equation of drying rate

The empirical equation for fluidised-bed paddy drying in the form of the equation of Page[10] developed by Sripawatakul[9] was used. It is written as follows:

$$MR = \exp(-xt^y) \qquad (2)$$

where $MR = (M - M_{eq})/(M_{in} - M_{eq})$
t = drying time, min
$x = 0.00163100\,T_{mix} - 1.16202\,(m_{mix}/hu) + 0.00415300\,(m_{mix}/hu)\,T_{mix} + 0.147383\ln(m_{mix}/hu) + 0.474743$
$y = -0.00322000\,T_{mix} - 0.835960\,(m_{mix}/hu) + 0.0203190\,(m_{mix}/hu)\,T_{mix} - 0.143150\ln(m_{mix}/hu) + 0.548493$

Equation (2) is similar to that developed by Soponronnarit and Prachayawarakorn[5] for higher specific airflow rate (m_{mix}/hu). It is valid for temperatures of 90 - 140°C and specific airflow rates of 0.03 - 0.16 kg/s/kg dry matter of paddy. The symbols are defined as follows:

M = moisture content of paddy at time t, decimal dry basis
M_{in} = moisture content of paddy at the inlet of drying section, decimal dry basis
M_{eq} = equilibrium moisture content, decimal dry basis
T_{mix} = air temperature at the inlet of drying section, °C
m_{mix} = airflow rate at the inlet of drying section, kg/s

During calculation, Equation (2) was differentiated with time, and finite difference was employed to obtain the solution. Equilibrium moisture content was determined using the equation developed by Laithong[11].

3. Equation of mass conservation

$$W_{f1,i}=R(M_i-M_f) + W_{mix} \quad (3)$$

where
- $W_{f1,i}$ = humidity ratio of outlet air at the i^{th} layer, kg water/kg dry air
- W_{mix} = humidity ratio of inlet air at the i^{th} layer, kg water/kg dry air
- M_i = moisture content of paddy at the inlet of i^{th} layer, decimal dry basis
- M_f = moisture content of paddy at the outlet of i^{th} layer, decimal dry basis
- R = ratio of dry mass of paddy to mass of dry air.

4. Equation of energy conservation

$$T_{f1,i} = [Q_1/m_{mix} + C_aT_{mix} + W_{mix}(h_{fg} + C_vT_{mix}) - W_{f1,i}h_{fg} + RC_{pw}T_{mix}]/(C_a + W_{f1,i}C_v + C_{pw}) \quad (4)$$

where
- $T_{f1,i}$ = temperature of outlet air at the i^{th} layer, °C
- Q_1 = heat loss, kW
- C_a = specific heat of dry air, kJ/kg °C
- C_v = specific heat of vapour, kJ/kg °C
- C_{pw} = specific heat of moist paddy, kJ/kg °C
- h_{fg} = latent heat of moisture vaporisation, kJ/kg

Average temperature and humidity ratio of the outlet air from n layers were determined by arithmetic mean.

For other calculations such as mixing of air streams, and consumption of energy at the fan and the heater, solutions can be achieved by the application of first law of thermodynamics.[5] The equations were solved by iteration. Firstly, the value of exit humidity ratio of air was assumed. The equations presented by Wilhelm[12] were used to determine properties of moist air.

The accuracy of the mathematical model was tested and found to be in good agreement with the experimental results. The model was employed to investigate optimum operating parameters such as air temperature, specific airflow rate, and fraction of air recycled. Details are available.[6]

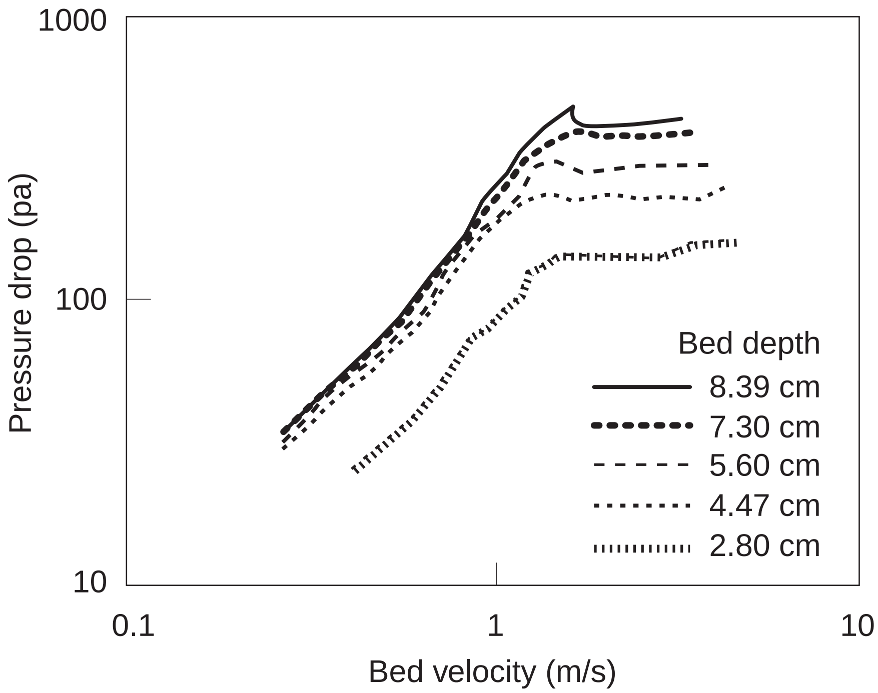

Fig 4. Relationship between bed pressure drop and bed velocity at different bed depths in fluidised-bed dryer.

PERFORMANCE OF FLUIDISED-BED PADDY DRYER

Minimum fluidised-bed velocity

From the experimental results reported,[5] the minimum fluidised-bed velocity for paddy is approximately 1.65 m/s and increases with moisture content. The relationship between pressure drop across the paddy bed and bed velocity is presented in Fig 4.

Experimental results from commercial fluidised bed dryers

Experimental results from commercial fluidised bed paddy dryers are summarized in Table 1.[13] Paddy qualities in terms of head yield and whiteness are all acceptable as compared to paddy dried by ambient air which is expected to obtain highest quality. Considering energy consumption, it is relatively low as compared to conventional hot air dryers, except a case 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 tempering process follows the fluidised-bed drying. In addition, as compared to ambient air drying, head yield can be increased 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

Laboratory investigation[14] recommended how to manage moist paddy by three processes in series, *ie*, fluidised-bed drying, tempering and ambient air ventilation. Experimental results show that after the three processes, moisture content is reduced from 33% to 16.5% within approximately 53 minutes. During the first process, a fluidised-bed dryer with inlet air temperature of 150°C was used to reduce the moisture content of paddy down to 19.5% within 3 minutes. Then the paddy was tempered for 30 minutes. Finally, it was cooled by ambient air (temperature and relative humidity of 30°C and 55-60%, respectively with air velocity 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

Experiment on paddy drying using fluidisation technique and paddy tempering following drying showed a significant spin-off.[15] Head yield increases

Table 1. Performance test results of commercial fluidised-bed paddy dryers.

Drying air temp. (°C)	Air recycled (%)	Inlet moisture of paddy (%db)	Outlet moisture of paddy (%db)	Outlet grain temp. (°C)	Electrical energy consumed ($MJ/kg\text{-}H_2O$)	Themal energy consumed ($MJ/kg\text{-}H_2O$)	Head yeild[c] (%)	Reference[d] head yield (%)	Whiteness[c]	Reference[d] whiteness	Testing hours	Drying capacity (ton/h)
115	69	22.0	20.1	54.0	0.83	7.80	53.2	57.4	40.3	44.4	5.0	9.5[b]
116	69	26.0	22.5	52.0	0.43	3.13	54.3	57.2	40.7	44.2	35.0	9.5[b]
120	69	28.7	22.5	54.0	0.26	2.57	53.9	53.9	40.0	40.1	46.0	9.5[b]
130	69	30.6	23.0	57.0	0.21	2.21	57.0	57.0	43.7	43.8	51.0	4.8[b]
150	53	27.0	21.0	63.0	0.15	3.90	48.1	56.2	36.8	42.6	29.0	4.8a

[a] Dryer with capacity of 2.5 - 5 tons/h, [b] Dryer with capacity of 5-10 tons/h,
[c] Dried in fluidized bed dryer, [d] Dried by ambient air

higher 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 as compared to that without tempering. Rice whiteness of dried paddy is mostly accepted provided that 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 has higher bad smell and lower whiteness of cooked rice. However, this may be solved by reducing tempering time down to 30 minutes. It is recommended for further research.

Conclusion

Fluidised-bed paddy drying has been developed for almost 7 years in Thailand. The first fluidised-bed paddy dryer was first commercialized in Thailand in 1995. It is probably the first commercial continuous fluidised-bed dryer for paddy drying. Since then, more than 90 commercial units with capacities of 5t/hour and 10 t/hour have been sold in Thailand, the Philippines, Indonesia, Malaysia and Taiwan.

A basic study including drying kinetics and factors affecting paddy quality, moisture reduction rate and energy consumption was conducted. Important results are presented in this paper. The performance of commercial fluidised-bed paddy dryer was also investigated and presented. Finally, a complete mathematical model for continuous fluidised-bed paddy drying was derived.

In conclusion, a fluidised-bed paddy dryer can be competitive with conventional hot air dryers especially at high moisture level, *ie*, low energy consumption, low cost and acceptable paddy quality. Important operating parameters are : drying air temperature of 140 - 150°C, fraction of air recycled of 0.8, air velocity 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% as compared to ambient air drying. For consumer acceptance, tested rice with fluidised-bed drying is not significantly different from that dried by ambient air.

Acknowledgements

Thanks are due to the Thailand Research Fund and the Australian Centre for International Agricultural Research for financial support.

References

1. Soponronnarit S, Wongvirojtana P, Nathakaranakule A and Prachayawarakorn S (1994) Maintaining paddy quality by appropriate ventilation under tropical climate. Proceedings of the 9th International Drying Symposium, Gold Coast, Australia.
2. Driscoll RH and Srzednicki GS (1991) Design for a complete grain drying system under Southeast Asian climates. Proceedings of the 12th ASEAN Technical Seminar on Grain Post-harvest Technology, Surabaya, 29-31 August 1989.
3. Sutherland JW and Ghaly TF (1992) Rapid fluid bed drying of paddy rice in the humid tropics. Proceedings of the 13th ASEAN Conference on Grain Postharvest Technology, Brunei Darussalam, 4-7 September 1990.
4. Tumambing JA and Driscoll RH (1993) Modeling the performance of continuous fluidized bed paddy dryer for pre-drying of paddy. Proceedings of the 14th ASEAN seminar on Grain Postharvest Technology, Philippines, 1991, pp 1-32.
5. Soponronnarit S and Prachayawarakorn S (1994) Optimum strategy for fluidized bed paddy drying. *Drying Technology* **12**, 1667-86.
6. Soponronnarit S, Prachayawarakorn S and Sripawatakul O (1996) Development of cross-flow fluidized bed paddy dryer. *Drying Technology* **14**, 2397-410.
7. Soponronnarit S, Yapha M and Prachayawarakorn S (1995) Cross-flow fluidized bed paddy dryer: prototype and commercialization. *Drying Technology* **13**, 2207-16.
8. Yapha M (1994) Design and testing of pilot continuous fluidized bed paddy dryer. Masters thesis, School of Energy and Materials, King Mongkut's Institute of Technology Thonburi, Bangkok, Thailand.
9. Sripawatakul O (1994) Study of drying paddy by cross-flow fluidization technique. Masters thesis, Faculty of Engineering, King Mongkut's Institute of Technology Thonburi, Bangkok, Thailand.
10. Page GE (1949) Factors influencing the maximum rate of drying shelled corn in layers. Unpublished thesis, Master of Science, Purdue University.
11. Laithong C (1987) Study of thermo-physical properties of rough rice. Masters thesis, King Mongkut's Institute of Technology Thonburi, Bangkok, Thailand.
12. Wilhelm LR (1976) Numerical calculation on psychrometric properties in SI units. *Transactions of the American Society of Agricultural Engineers* **19**, 318-21, 325.
13. Soponronnarit S, Prachayawarakorn S and Wangji M (1996) Commercial fluidized bed paddy dryer. Proceedings of the 10th International Drying Symposium, Krakow, Poland, 30 July - 2 August 1996, Vol. A, pp 638-44.
14. Soponronnarit S, Wetchacama S, Swasdisevi T and Poomsa-ad N (1999) Managing moist paddy by drying, tempering and ambient air ventilation. Accepted to be published in Drying Technology 17.
15. Soponronnarit S, Taweerattanapanish A, Wetchacama S, Kongseri N and Wongpiyachon S (1998) Spin-off from paddy drying by fluidization technique. Keynote paper presented at the 7th International Working Conference on Stored-Product Protection, Beijing, China, 14-19 October 1998.