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การจำลองแบบปัญหาทางคณิตศาสตร์ของการอบแห้งข้าวเปลือกด้วยเทคนิคผสมผสาน

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บทคัดย่อ

ในปัจจุบันได้มีการผลิตเครื่องอบแห้งฟลูอิไดซ์เบดเป็นเชิงการค้า และส่งออกไปยังหลายประเทศ ศักยภาพของเครื่องอบแห้งชนิดนี้ค่อนข้างสูงโดยเฉพาะเมื่อนำมาอบแห้งเมล็ดพืชที่มีความชื้นสูง เช่น ข้าว ข้าวนึ่ง ข้าวโพด และถั่วเหลือง อัตราการลดความชื้นของเครื่องอบแห้งชนิดนี้สูงกว่าเครื่องอบแห้งเมล็ดพืชที่ใช้กันทั่วไปในอุตสาหกรรม จากข้อดีดังกล่าวดังกล่าวทำให้เครื่องอบแห้งมีขนาดกะทัดรัดเมื่อเทียบกับความสามารถในการอบแห้งของเครื่อง ความสิ้นเปลืองพลังงานในการอบแห้งต่ำ คุณภาพของเมล็ดพืชหลังการอบแห้งด้วยเทคนิคนี้อยู่ในเกณฑ์ดี ในบทความนี้เป็นการบรรยายถึงงานวิจัยและพัฒนาการอบแห้งเมล็ดพืชด้วยเทคนิคฟลูอิไดซ์เบด โดยเริ่มตั้งแต่การศึกษาการอบแห้งแบบเป็นงวดในระดับห้องปฏิบัติการ จนมาถึงการพัฒนาเครื่องอบแห้งชนิดต่อเนื่องเพื่อผลิตเป็นเชิงการค้า นอกจากนี้ยังกล่าวถึงแบบจำลองทางคณิตศาสตร์ของระบบอบแห้งด้วยเทคนิคฟลูอิไดซ์เบดซึ่งประกอบไปด้วยขั้นตอนการอบแห้ง การพัก และการเป่าลมเย็น ในแบบจำลองดังกล่าวนี้ยังได้รวมสมการของข้าวเต็มเมล็ดซึ่งจะทำให้แบบจำลองที่พัฒนาขึ้นนี้มีประโยชน์สำหรับงานออกแบบหาเงื่อนไขในการอบแห้ง เพื่อให้ได้อัตราการผลิตและคุณภาพอยู่ในเกณฑ์ดี

คำสำคัญ: ข้าวเปลือก คุณภาพ ระบบอบแห้ง

MATHEMATICAL MODELLING AND SIMULATION OF FLUIDISED-BED DRYING, TEMPERING AND VENTILATION OF GRAINS

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ABSTRACT

The fluidized-bed grain dryer is now fully commercialized and exported to several countries. Its potential is great especially for high moisture grains such as paddy, parboiled rice, maize and soybean. Its drying rate is very fast as compared to conventional grain dryers. Consequently, the size of drying unit is very compact relative to its capacity. Its energy consumption is relatively low while grain quality is maintained. In this paper, the research and development effort on fluidised bed grain drying is described, starting with an experimental batch dryer and culminating with a commercial continuous-flow dryer. A mathematical model of the fluidised bed grain drying system including a series of drying, tempering, ambient air ventilation and head-rice equation is derived. The model provides the useful information about designing and operating condition for the drying system in order to optimize the drying capacity and quality, both of which show the contradict results.

Keywords: Drying system, paddy, quality

Introduction

It has been suggested that high moisture paddy should be dried quickly to approximately 23% moisture content (dry basis[1]) then subjected to ambient air drying in storage (Soponronnarit et al. 1994; Driscoll and Srzednicki 1991). 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 (1992) were probably the first research group who investigated feasibility of using fluidisation technique for paddy drying. Japanese researcher may have conducted similar research work before. Experimental results reported by Sutherland and Ghaly (1992) 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.

Soponronnarit and Prachayawarakorn (1994) have reviewed the research and development work on fluidised bed drying of grain, and conducted both experimental and simulation studies on batch fluidised bed drying of paddy. Soponronnarit et al. (1996) described the development of a cross-flow fluidised bed paddy dryer with a capacity of 200 kg/hour (Fig.1). 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%.

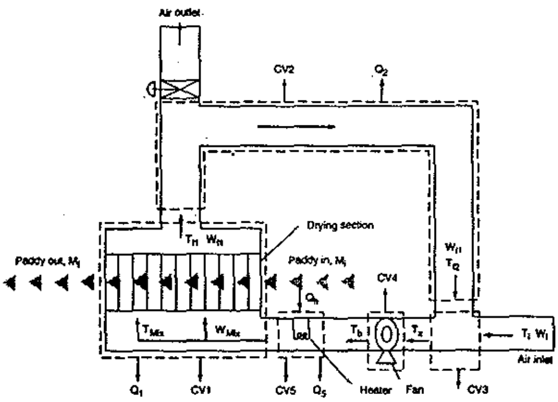

Figure 1 *Control volumes of continuous cross-flow fluidised bed drying system: ◀ grain flow; ← air flow; T, temperature; W, humidity ratio; M, grain moisture content; Q, heat; CV, control volume.*

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

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 as shown in Figure 2 (Soponronnarit et al. 1995). 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, mixed with ambient air and reheating to the desired temperature, respectively. The feed rate of paddy can be varied from less than 1 t/hour to more than 1.5 t/hour. More detail is given in Yapha (1994). 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 energy.

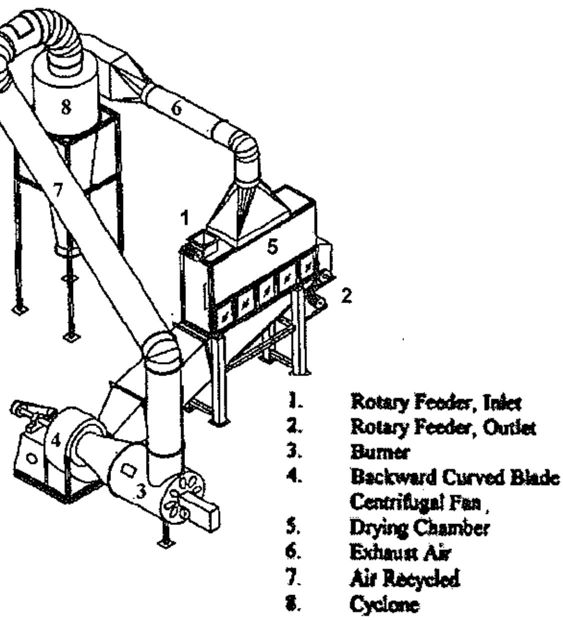


Figure 2 *Commercial fluidised-bed paddy dryer*

As a result of the success of the prototype, commercial fluidised bed paddy dryers with capacities of 5, 10 and 20 t/hour are now available. More than 200 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 or a cyclo-fan. Commercial cyclonic rice husk furnace is now available commercially. More than

200 units have been sold since the beginning of 1999.

Operation of the 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.

DEVELOPMENT OF MATHEMATICAL MODEL

It was assumed that there is thermal equilibrium between the drying air and the product, and that the air and grain flow were in plug type. Experimental results reported by Sripawatakul (1994) indicated that the flow regime of paddy was between near plug flow and high dispersion flow. Though dispersion was a known factor in the fluidised bed, the mathematical model assumed plug flow in order to simplify calculation. The model is similar to that presented by Soponronnarit and Prachayawarakorn (1994). Figure 1 shows control volumes (CVs) for the derivation of energy and mass balance equations.

Equation of mean residence time

The empirical equation of mean residence time of paddy developed by Sripawatakul (1994) 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 $hA\rho_p$ and can be applied to other grains.

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.

Equation for the drying rate

The empirical equation for fluidised bed paddy drying in the form of the equation of Page (1949), developed by Sripawatakul (1994), was used. It is written as follows:

$$MR = \exp\{-x(t/60)^y\} \quad (2)$$

where $MR = (M - M_{eq})/(M_{in} - M_{eq})$

t = drying time, s

$x = 0.00163100\ T_{mix} - 1.16202\ (m_{mix}/hu) + 0.00415300\ (m_{mix}/hu)\ T_{mix} + 0.147383\ \ln(m_{mix}/hu) + 0.474743$

$y = -0.00322000\ T_{mix} - 0.835960\ (m_{mix}/hu) + 0.0203190\ (m_{mix}/hu)\ T_{mix} - 0.143150\ \ln(m_{mix}/hu) + 0.548493$

Equation (2) is similar to that developed by Soponronnarit and Prachayawarakorn (1994) 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 (1987).

For the drying rates of maize and soybean, they are available in Soponronnarit et al. (1997) and Soponronnarit et al. (2001), respectively.

Equation of mass conservation

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

where $W_{fl,I}$ = 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_t = ratio of dry mass of paddy to mass of dry air.

Equation of energy conservation

$$T_{fl,i} = [Q_l/m_{mix} + C_a T_{mix} + W_{mix}(h_{fg} + C_v T_{mix}) - W_{fl,i} h_{fg} + R_t C_{pw} \theta_g]/(C_a + W_{fl,i} C_v + R_t C_{pw}) \quad (4)$$

where $T_{fl,i}$ = temperature of outlet air at the i^{th} layer, °C
θ_g = grain temperature, °C
Q_l = 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 [see Soponronnarit and Prachayawarakorn (1994) for details].

The equations were solved by iteration. Firstly, the value of exit humidity ratio of air was assumed. The equations presented by Wilhelm (1976) 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 for paddy drying and maize drying are available in Soponronnarit et al. (1996) and Soponronnarit et al. (1997), respectively.

Further development of the mathematical model

In simulation of multi-stage drying including the tempering between each stage, the moisture profile in a grain kernel at the end of each drying stage must be known. Unfortunately, the moisture profile in a grain kernel cannot be predicted by the empirical drying equations such as Equation (2). But, it can be determined only by using a theoretical equation, mostly described by the Fick's unsteady state diffusion equation in which an effective moisture diffusion coefficient is taken into account.

Poomsa-ad et al. (2002) developed the mathematical model for the simulation of multi-stage drying including the tempering between each stage. It was assumed that water moves in the combined radial and axial direction and paddy is an isotropic solid. The partial differential equation of moisture diffusion for a single paddy kernel considered geometrically to be a finite cylindrical shape can be written as follows:

$$\frac{\partial M}{\partial t} = D\left[\frac{\partial^2 M}{\partial r^2} + \left(\frac{1}{r}\right)\frac{\partial M}{\partial r} + \frac{\partial^2 M}{\partial z^2}\right] \qquad (5)$$

where D = effective moisture diffusion coefficient, m/s^2
r = coordinate along the radius of cylinder, m
z = coordinate along the length of cylinder, m

The initial and boundary conditions for paddy drying are given by

$$t = 0,\ 0 \le r \le r_o \quad M = M_{in} \text{ or } M = M(r,z)$$
$$-\ell \le z \le +\ell \quad M = M_{in} \text{ or } M = M(r,z)$$
$$t > 0,\ r = r_o \quad M = M_{eq}$$
$$z = \pm\ell \quad M = M_{eq}$$
$$t > 0,\ r = 0 \quad \frac{\partial M}{\partial r} = 0$$

where ℓ = half length of cylinder, m
r_o = radius of cylinder, m

The effective moisture diffusion coefficient described by the Arrhenius type equation is given as follows:

$$D = 5.41141\times10^{-6}\exp\left(\frac{-28436.4}{R(273.15+T)}\right) \quad (6)$$

where R = universal gas constant, kJ/kmol-K

For tempering process, moisture profile at the end of the first stage drying is used as the initial condition. During this period, the moisture inside a paddy kernel transports to the exterior surface, but it does not evaporate to the environment. The redistribution of moisture inside the kernel can be described again by Equation (5) with the new boundary and initial conditions as follows:

$$t = 0, \qquad M = M(r,z)$$

$$t > 0,\ r = r_o \qquad \frac{\partial M}{\partial r} = 0$$

$$z = \pm\ell \qquad \frac{\partial M}{\partial z} = 0$$

$$t > 0,\ r = 0 \qquad \frac{\partial M}{\partial r} = 0$$

The degree of uniformity of moisture content in this stage is described by the tempering index, I_c,

$$I_c = \frac{(M_{s,t} - M_{s,t=0})}{(M_{s,t=\infty} - M_{s,t=0})} \quad (7)$$

where M_s is the surface moisture content, decimal dry basis. Theoretically, the uniform distribution of moisture, corresponding to the tempering index of unity, required infinite time.

After tempering stage, the grains are cooled to room temperature, using ambient air temperature, to stop formation of yellow pigment. Yellowing can be a severe problem in rice drying because temperature stimulates the development of rice yellowness, a non-enzymatic browning reaction (Taweerattanapanish et al., 1999; Soponronnarit et al., 1998a; Yap et al., 1988). Ventilation was stopped when the grain temperature approached or was slightly above ambient air temperature. While the air ventilated through the heated grains, there was the simultaneous heat and mass transfer from the grain to air, making the air slightly warmer and more humid. The heat-transfer phenomenon in this unit was opposite to that occurring in the dryer section. Assuming that the air flowed through a thin bed in the cross-flow dryer, the outlet-air temperature, T_{fl}, is thus given by

$$T_{fl} = (C_a T_i + W_i(h_{fg} + C_v T_i) - W_i h_{fg} + R_t C_{pw}\theta_{in}) / (C_a + W_{fl} C_v + R_t C_{pw}) \quad (8)$$

where θ is the grain temperature (°C) and W_{fl} is the outlet humidity ratio at the ventilation unit. Using such a simplified assumption, the properties of air change insignificantly along the bed height, thereby providing economic computation by a single-step approach. For the moisture transport in the ventilation, it is calculated by using Equation (5) again, with the following initial and boundary conditions:

$t = 0, \quad M = M(r,z) \qquad t > 0, \; r = r_o \quad M = M_{eq}$

$z = \pm l \qquad M = M_{eq}$

In the determination of moisture reduction, the grain temperature is replaced in Equation (6), instead of the inlet-air temperature, because the grain temperature at the beginning of ventilation was approximately 50°C higher than the ambient-air temperature.

Head-rice yield equation

Poomsa-ad et al. (2001) reported that the amount of head rice yield related with tempering time, grain temperature or tempering temperature and the moisture content after fluidised-bed drying. A head rice equation was simply described by

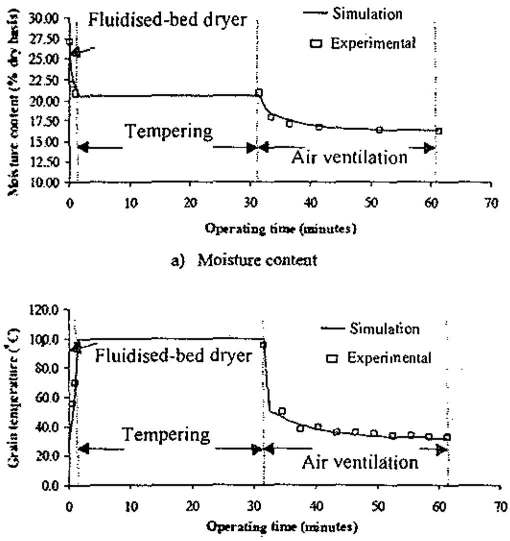
$$\mathbf{RHY = A + Bt + Ct^2} \qquad (9)$$

where $A = -39.232+8.4227M_f-0.34060T-0.029105TM_f$
$B = 25.945-1.1878M_f-0.2443T+0.012302TM_f$
$C = -0.33610+0.015028M_f+0.003259T$
$-0.00015762TM_f$

t is the tempering time (minute), M_f is the moisture content (%d.b.) after drying and T is the tempering temperature (°C).

SIMULATION RESULTS

Figure 3 shows the change of moisture content and grain temperature after passing through the units i.e. drying, tempering and ventilation in the process of paddy drying. This experiment was carried out with a batch fluidized-bed drying and the details were given in Poomsa-ad et al. (accepted to be published). As shown in this Figure, the moisture content is reduced from 27.5% d.b. to 22.5% d.b. in the fluidised-bed dryer followed the unchanged value of moisture content in the tempering stage. In the last stage, the moisture content is decreased to 17.5% d.b. The model proposed reasonably predicts the changes of moisture content and grain temperature at various units of the paddy drying process. As seen in Figure 3b, the temperature steeply drops during a small interval of ventilation, thus causing a high reduction of head rice yield, due to the thermal and moisture gradients, if the grains are not tempered. The poor head-rice yield can be seen in Figure 4 for zero tempering time, with a relative head-rice yield of 20% for the case of B. The relative head-rice yield is defined as the ratio of head-rice yield obtained by drying paddy at high temperature to that at ambient temperature. For the case of A, on the other hand, the head-rice yield quality does not drop although the sample is not subjected to temper.



a) Moisture content

b) Grain temperature

Figure 3 Comparisons of moisture content and grain temperature obtained from the experiment and prediction. (Poomsa-ad et al. (accepted to be published))

The insignificant reduction of head-rice yield for the case of 35% d.b. moisture content is probably attributed to the gelatinization effect, making paddy to withstand the milling forces. When the tempering time increases, the head-rice yield is improved and higher than that at zero tempering time. According to this result, it is questionable whether the paddy should be tempered for how long after drying with fluidised-bed dryer. To answer such a question, the proposed model is used to estimate the suitable tempering time. The criterion indicating the appropriate tempering time is related to the tempering index. Poomsa-ad et al. (2002) recommended the tempering index of 0.95, corresponding to the calculated tempering time of 35 minutes for high-temperature drying. This agrees with the experiment results shown in Figure 4, indicating insignificant change of head-rice yield after tempering for 30 minutes. In addition to the aforementioned quality, the fastest drying rate at the subsequent stage is achieved, giving the benefit of effective energy utilisation. From this figure, it also shows that the head-rice yield equation when included in the heat and mass transfer equations reasonably explains the quality change with the tempering time.

The similar result was also reported by several workers (Steffe et al., 1979; Soponronnarit et al., 1998b; Soponronnarit et al., 1999), showing a higher head-rice yield when the tempering was included between drying stages.

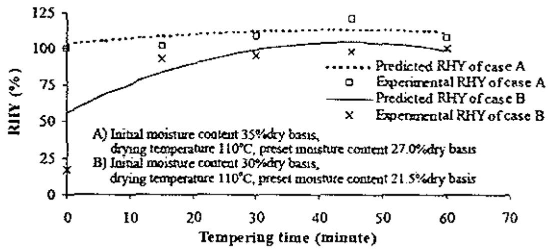


Figure 4 Effect of tempering time on relative head-rice yield
(Poomsa-ad et al. (accepted to be published))

SIGNIFICANCE OF SIMULATION RESULTS

Reducing moisture content of paddy by using only fluidised-bed dryer seems an inappropriate method since the transport of water is controlled by internal resistances, resulting in wastage of energy. Besides, the amount of broken rice is enormous, due to excessive stresses produced inside the kernel, and the colour of white rice changes from white to yellow, causing by the non-enzymatic browning reaction (Soponronnarit and Prachayawarakorn, 1994; Sutherland and Ghaly, 1992). To optimise the drying time and energy consumption, along with high head-rice yield, moist paddy should be followed with three stages in series i.e. fluidised bed, tempering and ambient air ventilation to remove its moisture content to a certain level for safe storage. Both experiments and simulations agree well that fluidised-bed dryer, with inlet air temperature of 150°C, is used to decrease the moisture content of paddy to 19.5% d.b. followed with tempering for 30 minutes. In the last stage, the paddy is 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. Under the specified conditions, the thermal and electrical energy consumptions were in the respective ranges of 5-7 MJ/kg-water evaporated and 0.54-0.61 MJ/kg-water evaporated. For drying paddy within high moisture range using fluidized bed technique only, it was reported by Soponronnarit (2000) that energy consumption was lower, i.e. 2.2-3.9 MJ/kg-water evaporated in terms of thermal energy and 0.15-0.43 MJ/kg-water evaporated in terms of electrical energy. Under proper conditions such as high initial moisture content of paddy (higher than 30%) 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 insignificantly different from that dried by ambient air.

Conclusion

Fluidised bed grain drying has been developed for almost 10 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 200 commercial units with capacities of 5, 10 and 20 tons/hour have been sold in Thailand, Cambodia, Indonesia, Laos, Malaysia, Mexico, Myanmar, the Philippines, Taiwan and Venezuela.

A basic study including drying kinetics and factors affecting grain quality, moisture reduction rate and energy consumption was conducted for paddy, maize and soybean. Important results are presented in this paper. Finally, a complete mathematical model for the fluidised bed grain drying system including a series of drying, tempering and subsequent ventilation was derived.

In conclusion, the fluidised bed paddy dryer is competitive with conventional hot air dryers especially at high moisture level, i.e. 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 30%) 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.

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References

Driscoll, R.H. and Srzednicki, G.S., 1991. **Design for a complete grain drying system under Southeast Asian climates.** Proceedings of the 12th ASEAN Technical Seminar on Grain Post-harvest Technolog: 29-31 August 1989; Surabaya; Indonesia.

Laithong, C., 1987. **Study of physico-thermal properties of rough rice.** [Master's thesis]. Bangkok. Thailand: King Mongkut's Institute of Technology Thonburi.

Page, G.E., 1949. **Factors influencing the maximum rate of drying shelled corn in layers.** [Master of Science]: Purdue University.

Poomsa-ad, N., Soponronnarit, S., Prachayawarakorn, S. and Terdyothin, A. 2002. Effect of tempering on subsequent drying of paddy using flidisation technique. **Drying Technology** 20: 195-210.

Poomsa-ad. N, Soponronnarit, S., Terdyothin, A. and Prachayawarakorn, S., 2001. **Head rice yield after drying by fluidization technique and tempering. Proc.** the 2nd Asian-Oceana Drying Conference;20-23 August 2001; Penang, Malaysia.

Poomsa-ad. N., Soponronnarit, S. and Prachayawarakorn, S. Investigation on head-rice yield and operating time in drying process: Experiment and Simulation. **Journal of Stored Product Research.** (Accepted to be published)

Soponronnarit, S., 2000. Fluidised bed grain drying. In: Mujumdar, A. **and Suvachittanont, S. (Eds.), Developments in Drying Vol. II. Drying of Food and Agro-Products** : 135-148

Soponronnarit, S. and Prachayawarakorn, S. 1994. Optimum strategy for fluidized bed paddy drying. **Drying Technology** 12: 1667-1686.

Soponronnarit, S., Kittiporn, K. and Prachayawarakorn, S. 1997. Appropriate operating parameters for fluidized bed corn drying. **RERIC International Energy Journal** 19: 1-13.

Soponronnarit, S., Prachayawarakorn, S. and Sripawatakul, O., 1996. Development of cross-flow fluidized bed paddy dryer. **Drying Technology** 14: 2397-2410.

Soponronnarit, S., Srisubati, N., Yoovidhya, T., 1998a, Effect of temperature and relative humidity on yellowing rate of paddy. **Journal of Stored Products Research.** 34: 323-330.

Soponronnarit, S., Swasdisevi, T., Wetchacama, S. and Wutiwatchai, W., 2001, Fluidised bed drying of soybeans. **Journal of Stored Product Research.** 37: 133-151.

Soponronnarit, S., Taweerattanapanish, A., Wetchacama, S., Kongseri, N. and Wongpiyachon, S. 1998b. **Spin-off from paddy drying by fluidization technique.** Keynote paper in

Proc. at the 7th International Working Conference on Stored-Product Protection;14-19 October 1998; Beijing, China.

Soponronnarit, S., Wetchacama, S., Swasdisevi, T. and Poomsa-ad, N., 1999, Managing moist paddy by drying, tempering and ambient air ventilation. **Drying Technology** 17: 335-344.

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; 1-4 August 1994; Gold Coast; Australia.

Soponronnarit, S., Yapha, M. and Prachayawarakorn, S., 1995, Cross-flow fluidized bed paddy dryer: prototype and commercialization. **Drying Technology** 13: 2207-2216.

Sripawatakul, O., 1994. **Study of drying paddy by cross-flow fluidization technique**.[Master's thesis Faculty of Engineering]. Bangkok. Thailand: King Mongkut's Institute of Technology Thonburi.

Steffe, J.F., Singh, R.P. and Bakshi, A.S., 1979, Influence of tempering time and cooling on rice milling yields and moisture removal. **Trans.of the ASAE**. 17: 1214-1218.

Sutherland, J.W. and Ghaly, T.F., 1992. **Rapid fluid bed drying of paddy rice in the humid tropics**. Proceedings of the 13th ASEAN Conference on Grain Post-harvest Technology. 4-7; September 1990; Brunei Darussalam.

Taweerattanapanish, A., Soponronnarit, S., Wetchacama, S., Kongseri, N., Wongpiyachon, S., 1999. Effects of drying in head rice yield using fluidization technique. **Drying Technology** 17: 345-353.

Tumambing, J.A. and Driscoll, R.H. 1993. **Modeling the performance of continuous fluidized bed paddy dryer for rapid pre-drying of paddy.** *Proceedings of the 14th ASEAN seminar on Grain Post-harvest Technology*; 5-8 November 1991; Manila, Philippines.

Wilhelm, L.R. 1976. Numerical calculation on psychrometric properties in SI units. **Transactions of the American Society of Agricultural Engineers** 19: 318-321, 325

Yapha, M., 1994. **Design and testing of pilot continuous fluidized bed paddy dryer.** [Master's thesis, School of Energy and Materials]. Bangkok. Thailand; King Mongkut's Institute of Technology Thonburi.

Yap, A.B., Juliano., B.O., Perez. C.M. 1988. **Artificial yellowing of rice at 60°C. In: Naewbanij**. J.O. (Ed).Proceedings of the Eleventh ASEAN Technical Seminar on Grain Postharvest Technology; 23-26 August, 1988; Kuala Lumpur, Malaysia. ASEAN Grain Postharvest Programme. Bangkok. Thailand.

ประวัติส่วนตัว

ศาสตราจารย์ ดร.สมชาติ โสภณรณฤทธิ์ เกิดเมื่อวันที่ 27 พฤษภาคม พ.ศ. 2495 ที่กรุงเทพมหานคร สำเร็จการศึกษาระดับปริญญาตรีเกียรตินิยมอันดับ 1 จากมหาวิทยาลัยขอนแก่นด้านวิศวกรรมศาสตร์ สาขาวิศวกรรมเกษตร ปริญญาโทจาก Asian Institute of Technology และระดับปริญญาเอกด้าน Agricultural Process Engineering จาก Ecole National Superieur Agronomique de Toulouse สมรสกับนางเจิมใจ (อัศวเสนา) โสภณรณฤทธิ์ มีบุตร 3 คน คือนางสาวกุลยา นางสาวกชพร และนายกานต์ โสภณรณฤทธิ์ ปัจจุบันดำรงตำแหน่งศาสตราจารย์ระดับ 11 คณะพลังงานและพัสดุ มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี และรักษาการคณบดีคณะวิศวกรรมศาสตร์ มหาวิทยาลัยมหาสารคาม ปี พ.ศ. 2539 ได้รับรางวัลนักวิจัยดีเด่นแห่งชาติ สาขาวิศวกรรมศาสตร์และอุตสาหกรรมวิจัย จากสำนักงานคณะกรรมการวิจัยแห่งชาติ และได้รับทุนเมธีวิจัยอาวุโส สกว.รุ่นที่ 2 พ.ศ. 2539-2542 ปี พ.ศ. 2543 ได้รับรางวัลนักวิทยาศาสตร์ดีเด่น และได้รับทุนทุนเมธีวิจัยอาวุโส สกว.รุ่นที่ 5 พ.ศ. 2543-2546 ในปี 2546 ได้รับรางวัลนักวิทยาศาสตร์ขององค์การยูเนสโก (2003 UNESCO SCIENCE PRIZE) และในปี พ.ศ. 2547 ได้รับพระราชทานเครื่องราชอิสริยาภรณ์ ม.ป.ช. มหาปรมาภรณ์ช้างเผือก

ผลงานเด่นได้แก่ การร่วมมือกับภาคเอกชนพัฒนาเครื่องต้นแบบสำหรับอบแห้งข้าวเปลือกและเตาเผาแกลบ จนนำไปสู่การจดสิทธิบัตร ผลิตขาย และส่งออกอย่างแพร่หลาย ปฏิบัติการหลังการเก็บเกี่ยวเป็นขั้นตอนที่สำคัญต่อคุณภาพของผลผลิต โดยเฉพาะขั้นตอนการลดความชื้นซึ่งสำคัญต่อการรักษาคุณภาพ และลดการสูญเสีย ผลผลิตรวมของข้าวเปลือกมีมูลค่ากว่า 80,000 ล้านบาทต่อปี หากสามารถลดการสูญเสียเพียง 1% ก็สามารถลดความเสียหายได้ถึง 800 ล้านบาท การอบแห้งโดยเทคนิคฟลูอิไดเซชัน (fluidization) เป็นวิธีการใหม่ที่นำมาใช้ลดความชื้นของข้าวเปลือก สามารถลดทั้งระยะเวลาและค่าใช้จ่ายในการผลิต นอกจากนี้เตาเผาแกลบไซโคลน (cyclone) ที่พัฒนาขึ้น สามารถลดการใช้น้ำมันเชื้อเพลิงได้อย่างน้อยปีละ 200-300 ล้านบาท และได้มีเอกชนหลายบริษัทนำต้นแบบเครื่องอบแห้งฟลูอิไดซ์เบดและเตาเผาแกลบไซโคลนไปผลิตขายเชิงการค้าทั้งในประเทศและต่างประเทศแล้วไม่ต่ำกว่า 500 เครื่อง เป็นมูลค่าไม่ต่ำกว่า 500 ล้านบาท