시뮬레이션에 의한 循環式 벼 乾燥

-純乾燥 및 템퍼링 時間의 影響-

Continuous Flow Rice Drying Using Simulation

-Resident and Tempering Time Effects-

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摘 要

循環式 벼 乾燥過程을 乾燥-템퍼링의 연속 과정으로 간주하여 이를 解析할 수 있는 시뮬레이션 모델을 개발하였으며, 시뮬레이션 결과치와 실험치가 잘 일치하였다.

특히 벼의 薄層乾燥方程式으로 Page형의 方程式과 水分擴散方程式을 이용한 모델을 비교하였으며, 수분확산계수는 白米部, 쌀겨部 및 왕겨部로 나누어 고려하였다.

시뮬레이션 모델을 이용하여 純乾燥 및 템퍼링 時間이 乾燥速度, 所要에너지 및 穀物品質에 미치는 영향을 分析하고 적절한 純乾燥時間 및 템퍼링 시간을 제시하였다.

I. Introduction.

Rice is harvested at a high-moisture content and must be dried to prevent spoilage. In Korea, most of mechanical rice drying is done with dual column continuous flow on-farm dryer operating in crossflow mode. A typical continuous flow on-farm dryer consists of holding bin, drying section, and mechanism for recirculating rice. Rice is dried during flowing down through the drying section and then is held in the holding bin. Individual rice kernel is alternately dried and held several times.

Holding of this sort is referred to as tempering and the holding period as the tempering time. Exposed time to drying air per pass is referred to as resident time. It takes 10 to 20 passes for the moisture content of rice to be reduced to a safe storage level. These resident and tempering times affect on dryer performance; drying rate, energy requirments and quality.

Analysis of grain drying process using simulation has been carried out by various investigators (Henderson and Henderson (1968), Thompson et al. (1968), Bakker-Arkema et al. (1974), Ingram (1976)).

Most of these studies have been conducted on a commercial dryer or modeling of corn drying.

Wang (1978) modified MSU program (Bakker-Arkema et al. (1974)) to simulate cross-flow rice dryer. Bakshi et. al (1978) also used a modified MSU program to predict moisture content in crossflow rice dryer. They reported that predicted moisture was always higher than the observed moisture and a new computer program needed to be developed for simulating rice drying in a corss-

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** Agricultural Engineering Dept., University of California, Davis flow dryer. Singh et,al. (1981) developed a simulatin program for crossflow rice drying considering hourly variations of ambient temperature and humidity. Thompson et al. (1981) modified the above Singh's model to simulate air recirculation and to estimate optimum levels of air recirculation.

Internal diffusion of mass within rice kernel was neglected in the above rice drying simulations.

Diffusion equation was used to simulate concurrent rice dryer (Walker (1978), Zahed (1982), Bakker-Arkema (1983)).

Numerous researchers have considered rice tempering and resident time.

Ramage (1958) reported that high temperature (65.6°C) could be used successfuly if the rice was uniformly exposed and the resident time for each pass was kept short. Wassermann (1964) in tempering test concluded that rice cooled to 24°C immediately after drying required 6hr for adequate tempering, but only 4hr were required for tempering rice at 41°C. Wassermann et al. (1965) in the test for the effects of drying air temperature and number of passes on head rice yields and drying time reported that when number of pass was increased with constant temperature, drying was faster and head rice yield was higher. Calderwood and Webb (1971) reported that reducing resident time from 25 to 15min lowered drying time an average of 32% and milling yield was somewhat higher for rice dried with the reduced resident time. Beeny and Chin (1970) concluded in multipass drying test of paddy that as the number of passes were increased milling yield improved and drying time were greatly reduced. Tempering duration was found to have a greater effect on head rice yield improvement than the number of passes. Itoh and Terao (1974a) concluded that the rate of drying increased with longer tempering times and that qualities such as cracking and germination were closely related to the length of the tempering period. Steffe et al. (1979) in considering tempering time from 0.58 to 24hr concluded that when using 38°C air and 20min drying periods, a 35min tempering time was sufficient and in using 38°C air and 35min drying periods or 50°C air and 20min periods, tempering times of 3hr were satisfactory and shorter times might be adequate. Resident times used in continuous flow rice dryer in Korea range from 10 to 20min and tempering times from 30 to 75min. Establishing adequate resident and tempering time is very important for determining optimum operational conditions and design criteria. Objectives of this study were to develop a simulation model for the drying process in a continuous flow on-farm rice dryer including tempering and to discuss the effects of resident and tempering time on drying rate, grain temperature and energy requirements.

II. Mathematical Model

The crossflow drying model developed by Bakker-Arkema et al. (1974) were used with modifications. Unknowns are air temperature (T), absolute humidity (H), rice temperature (θ) and average moisture content ($\overline{M}$).

$$\frac{\partial T}{\partial x} = -\frac{ha \quad (T-\theta)}{G_a(c_a + c_v H)} \tag{1}$$

$$\frac{\partial \theta}{\partial y} = \frac{ha\,(T-\theta)}{G_p(c_p + c_w M)} - \frac{h_{fg} + c_v(T-\theta)}{G_p(c_p + cwM)}$$

$$\cdot G_a \cdot \frac{\partial H}{\partial x} \qquad (2)$$

$$\frac{\partial H}{\partial x} = -\frac{G_p}{G_a} \frac{\partial M}{\partial y} \qquad (3)$$

$$\frac{\partial M}{\partial y} = \text{appropriate thin layer equation} \quad (4)$$

In this study, two computer programs were used.

In the first program, the following thin layer equation, called Page's equation, for medium grain rough rice developed by Wang (1978) was used in drying rate form

$$\frac{\partial \overline{M}}{\partial t} = -K\,(\overline{M} - Me) \qquad (5)$$

$$\text{where} \quad K = 60 \cdot P^{\frac{1}{Q}} \cdot Q \cdot [\,-\ell n(MR)]^{\frac{Q-1}{Q}}$$

$$P = 0.01579 + 0.0001746T - 0.01413RH$$

$$Q = 0.6545 + 0.002425T + 0.07867RH$$

The Equation (6) was obtained from Equation (5) by replacing ∂t by $\partial y/V_p$

$$\frac{\partial \overline{M}}{\partial y} = -\frac{K}{V_p}\,(\overline{M} - M_e) \qquad (6)$$

A finite difference technique similar to that developed by Von Rosenberg et al. (1977) was used to solve the above four simultaneous Equations (1), (2), (3), and (6).

In the second program, the liquid diffusion equation developed by Steffe and Singh (1980) was used to predict the thin-layer drying of rough rice. The differential equation with boundary and initial conditions were:

$$\frac{\partial M}{\partial y} = \frac{D_m}{V_p}\left(\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r}\right) \qquad (7)$$

$$m = 1, 2, 3$$

$$\frac{\partial M}{\partial r} = 0; \quad r = 0, \quad t \geqslant 0 \qquad (8)$$

$$M = Me; \; r = R_3, \quad t > 0 \qquad (9)$$

$$M = Mo; \; 0 \leqslant r \leqslant R_3, \; t = 0 \qquad (10)$$

Rough rice kernel was considered to be a sphere (starch endosperm) surrounded by two concentric sphere (bran and hull). The Crank-Nicolson finite differance technique (Crank and Nicolson, 1947) was employed to solve the diffusion equation (7) using the value of the diffusivity of the different kernel component and the size of the rice kernel component radii. The equivalent radii for medium grain rough rice were found by Bakker-Arkema (1983) and could be summerized in Table 1.

Diffusivity for the rough rice components were found by Steffe and Singh (1980a) as

$$D_1 = 2.57 \times 10^{-3} \mathrm{EXP}(-2.88 \times 10^3/\theta_a)$$

$$D_2 = 7.97 \times 10^{-1} \mathrm{EXP}(-5.11 \times 10^3/\theta_a)$$

$$D_3 = 4.84 \times 10^2 \; \mathrm{EXP}(-7.38 \times 10^3/\theta_a) \quad (11)$$

Average drying rate for individual rice kernel were evaluated as (Ingran, 1976)

$$\frac{\partial \overline{M}}{\partial y} = \frac{3}{V_p} \frac{D_3}{R_3} \left.\frac{\partial M}{\partial r}\right|_{r = R_3} \qquad (12)$$

The same technique as that in the first program was applied to solve the Equation (1), (2), (3), and (12)

The rough rice tempering model is basically an extention of the rough-rice drying model. During tempering, the moisture gradient occured during drying is equalized. It was assumed that the rice did not change in average moisture content or the rough rice surface was impervious to moisture flow. The tempering process was analyzed by the equation (7) and (11) with the following boundary and initial conditions (Steffe and Singh, 1980b)

$$\frac{\partial M}{\partial r} = 0; \quad r = R_3, \qquad t > 0 \tag{13}$$

$$M = M(r); \; 0 \leqslant r < R_3, \; t=0 \tag{14}$$

The following equlibrium moisture content equations, taken from Zuritz (1978), were used:

For $T < 42.5^\circ C$

$$M_e = 0.01 \left[\frac{(-\ln(1-RH)\, T_a)}{(1-T_a/647.1)^A \times B}\right]^{\frac{1}{C(T_a)^D}} \tag{15}$$

where $A = -23.438$

$B = 2.667 \times 10^{-7}$

$C = 4.0 \times 10^5$

$D = -2.1166$

For $T \geqslant 42.5^\circ C$ (Zuritz (1979)

$$M_e = \frac{\ell n\,(-\ell n\,(RH)) - \ell n(2.387 \times 10^9 T_a^{-3.444})}{-2.118 \times 10^{-2} T_a^{1.1852}} \tag{16}$$

The following convective heat transfer coefficient equation in a packed bed of medium grain rough rice developed by Wang (1978) was used:

$$h = 0.00718 G_a^{1.2997} \tag{17}$$

The latent heat of vaporization of rough rice developed by Wang (1978) based on the EMC data determined by Zuritz (1978) was utilized. This equation was:

$$h_{fg} = (1547.84 - 1.46T)\overline{M}^{-0.346} \tag{18}$$

The thermal and physical properties of medium grain rough rice and air used in simulation model were shown in Table 1.

Table 1. Thermal and Physical properties of medium grain rough rice and air.

Properties	Symbol	Values	
Specific heat of dry rice	c_p	0.9209 (kJ/kg K)	(1)
Specific surface area	a	1040 (m^2/m^3)	(2)
Density of dry rice	ρ	499.7 (Kg/m^3)	(1)
Radius of white rice	R_1	$0.142*10^{-3}$ (m)	(3)
Radius of brown rice	R_2	$0.150*10^{-3}$ (m)	(3)
Radius of rough rice	R_3	$0.161*10^{-3}$ (m)	(3)
Specific heat of dry air	c_a	1.0069 (kJ/kg K)	(4)
Specific heat of liquid water	c_w	4.1868 (kJ/kg K)	(4)
Specific heat of water vapor	c_v	1.8757 (kJ/kg K)	(4)

(1) Wratten et al. (1969)
(2) Wang (1978)
(3) Bakker-Arkema et al. (1983)
(4) ASAE Year book (1983)

III Model validation

The cross-flow rice dryer has previously been studied for medium-grain rough rice by some researchers. Comparison between the experimental results from several of these studies and the simulation results were presented in Table 2

Test 1 to test 6 were single pass drying tests. Test 7 was the multipass drying test with 11 min resident time and 12 min tempering time for each pass. Final moisture content was obtained after 20th drying pass. Test 8 was the two pass drying with 20 min resident time per pass and one 60 min tempering.

Tempering processes were included in the multipass simulation using diffusion equation and not included for the case of Page's equation

The average deviation of moisture content in the first program using Page's thin layer drying equations was 0.82% wb and in the second program using diffusion equation 0.41% wb.

Fig. 1 showed the plots of the experimental and the simulated moisture content versus drying time for test 7. Maximum difference between experimental and simulated moisture content was 0.88% wb. in the first program and 0.48% wb. in the second program, respectively. The moisture content simulated by the first program showed slightly lower values than the actual in the beginning of the drying periods and then higher values. In the case of the second program the simulated values were lower than the actual values through the whole drying periods.

Conclusively, the above average deviations and differences in moisture content in the two programs were small enough to be acceptable.

Table 2. Comparison of experimental and simulated result of medium-grain rough rice drying in cross-flow dryer.

Test No.	Hight of grain column (m)	Thickness of grain column (m)	Airflow rate (cmm/m^2)	Grain flow rate (m/hr)	Resident time (min/pass)	Drying air temp. ($^\circ$C)	Iintial moisture content (%, wb.)	Final moisture content at outlet (%, wb.)				
								Experimental	Simulated			
									Page's Eqn.		Diffusion Eqn.	
									Value	Difference	Value	Difference
1*	1.2	0.2	24.0	1.24	58	50.0	22.3	18.03	17.00	1.03	17.01	1.02
2*	1.2	0.2	24.0	1.24	58	48.9	22.0	17.36	15.71	1.65	16.94	0.42
3*	1.2	0.2	24.0	1.24	58	48.9	17.9	14.31	13.83	0.48	13.77	0.54
4*	1.2	0.2	24.0	1.24	58	48.0	17.2	13.04	13.24	-0.2	13.17	-0.13
5*	1.2	0.2	24.0	1.24	58	43.3	19.4	15.75	15.48	0.27	15.69	0.06
6**	16.75	0.3	33.8	33.5	30	49.4	19.1	17.36	16.12	1.24	16.34	1.02
7+	1.0	0.25	13.7	5.4	11	40.0	27.5	18.85	19.75	-0.9	18.82	0.03
8++	–	0.07	21.3	–	20	38.0	23.7	19.45	–	–	19.47	-0.02

* Data for pilot-scale cross-flow dryer (Bakshi, et al., 1978)

** Data for commercial cross-flow dryer (Singh, et al.,1981)

\+ Data for continuous-flow on-farm dryer (Han, 1985). Final misture contents were obtained after 7-hr drying period (after 20th drying pass with 11-min resident time per pass and 19th tempering pass with 12-min tempering time per pass)

++ Data for experimental fixed bed two pass drying with 20-min resident time per pass and 60-min. tempering period (Steffe, et al. 1979)

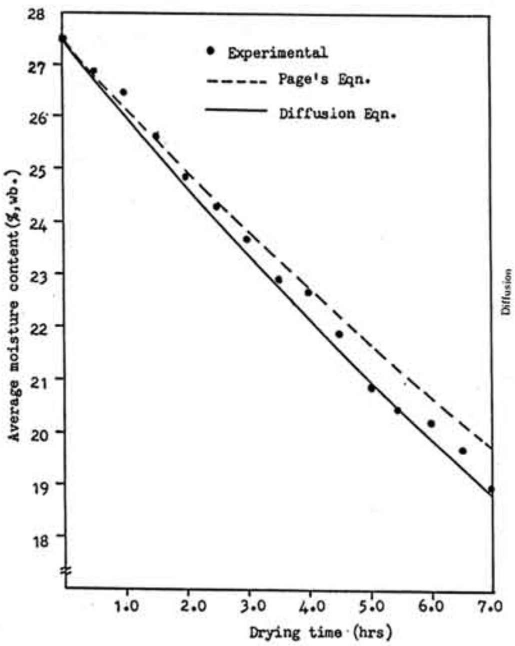

Fig. 1. Comparison of experimental and simulated average moisture content for Test No. 7

IV. Simulation procedure

Brook and Bakker-Arkema (1980) listed the advantages of using the diffusion equation in simulation program: First, it is easily applicable to a number of agricultural products for which a diffusivity is known. Second, the assumed shape of the kernel can be easily changed to represent a sphere, cylinder, or other shape. Third, the diffusion model can be used to approximate moisture distribution within the kernel. Considering the above, the second program using diffusion equation was used to predict continuous flow on-farm dryer performance.

A. Drying conditions

Using the second program, a series of drying tests were performed. Drying simulations were made for selected resident times, tempering index and drying air temperatures. These values were:

Resident time (min.) : 15, 20, 30, 35
Tempering index (%) : 60, 80, 90, 95
Drying air temperature (°C): 42, 50, 54

Tempering index was defined as the following equation.

$$I_c = \frac{M(\ell, t) - M(\ell, 0)}{M(\ell, \infty) - M(\ell, 0)} \tag{19}$$

Where ℓ refers to the outer node of rough rice kernel. The above definition of I_c was a modified form of that defined by Steffe et al. (1980 b). This number varies from zero to one as tempering proceeds from time zero to infinity.

The following conditions were assumed for all simulated drying tests:

Grain type:
medium-grain rough rice
Initial moisture content: 24%, wb.
Final moisture content: 16%, wb.
Ambient air temperature: 20°C
Ambient relative humidity: 65%
Air flow rate: 14.3 cmm/m²
Initial grain temperature: 20°C

B. Energy requirements

Total energy requirements included energy to heat the drying air and operate the fan. Heat energy requirements were evaluated from enthalpy balance on the air flowing through the heating furance assuming an 70% efficiency (Farmer (1972)):

$$E_a = \frac{G_a\,(c_a + c_v H)\,(T_{in} - T_{amb})\,td}{0.70\,(M_o - M_f)\,\rho X_c} \tag{20}$$

Fan energy requirements were calculated

by the following equation assuming 70% electrical-machanical conversion efficiency of motor and 50% fan efficiency (Farmer (1972))

$$E_f = \frac{0.06Q_a \Delta P t_d}{0.35\,(M_o - M_f)\rho X_c} \qquad (21)$$

The following pressure drop equation through packed bed of rough rice was derived by Zahed (1982) using experimental data from Rumsey et al. (1978)

$$\Delta P = 10357.8\,(Q_a/60)^{1.3877} X_c \qquad (22)$$

Substituting Equation (22) into Equation (21), Equation (23) could be obtained.

$$E_f = \frac{2.1178 Q_a^{2.3877}\, t_d}{0.35\,(M_o - M_f)\,\rho} \qquad (23)$$

C. Rice quality parameters

The following drying characteristics were considered as indicators of grain quality:

1. Maximum average rice temperature
2. Maximum drying rate
3. Head rice yield ratio

Assumed limits for each of these grain parameters were 38°C (Steffe et al., (1979)) and 1.5% wb./hr (Ban (1971)) respectively.

Singh et al. (1980) derived head yield equation as a function of resident time and drying air temperature using the data on milling quality of rice from Stipe et al. (1973).

$$HR = e^{-K_1 t} \qquad (24)$$

where HR=actual head yield/initial head yield

$K_1 = 1.9103*10^{21}\,\mathrm{EXP}\,(-1.7748*10^4/T_a)$

Based on this equation, head yield changes of rice during drying were simulated.

V. Simulation results and discussion

A. Moisture removal and redistribution

Representative grain moisture profiles for various tempering levels were presented in Fig. 2. As expected, faster drying was occured when tempering time was longer. In the case of 60% tempering level, average moisture content reached to 16% wb. after the seventh pass drying but in all other tempering levels after the sixth. The effects of tempering on moisture removal may be determined by considering total amount of moisture removed when drying from 24% wb. to 16% wb. Results for 50°C air and 20 min resident time per pass were presented in Table 3. Average drying rates for total resident time required

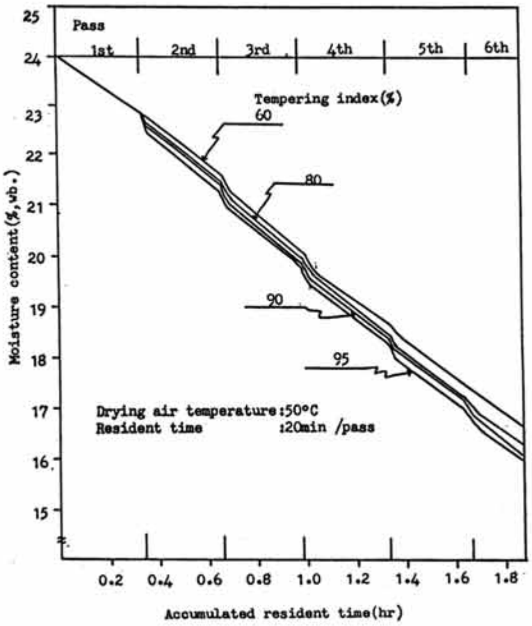

Fig. 2. Tempering effect on moisture content variations.

Table 3. Average drying rate for total resident time required to dry to 16% wb. with 50°C-drying air and 20 min resident time per pass, depending on various tempering levels.

Tempering index (%)	Total tempering time (hr)	Average Drying rate (%, wb./hr)
60	1.25	3.95
80	2.65	4.07
90	4.25	4.18
95	6.15	4.23

for the final moisture content of 16% wb. was increased with tempering time.

During tempering after 20 min drying with 50°C air, the moisture changes within the kernel were presented in Fig. 3. As the tempering time increased, the moisture contents at any point within the kernel approached to average value and moisture distribution was equalized. The surface moisture content of rough rice was more rapidly changed than that at other points. Table 4 showed that the moisture distribution within the kernel after the fifth tempering pass with various tempering periods (index) per pass. Moisture difference between the surface and center of rough rice was 10.4% wb. right after the first pass of drying but reduced to the range from 1.1% wb. to 5.7% wb. depending on tempering levels after the fifth tempering pass.

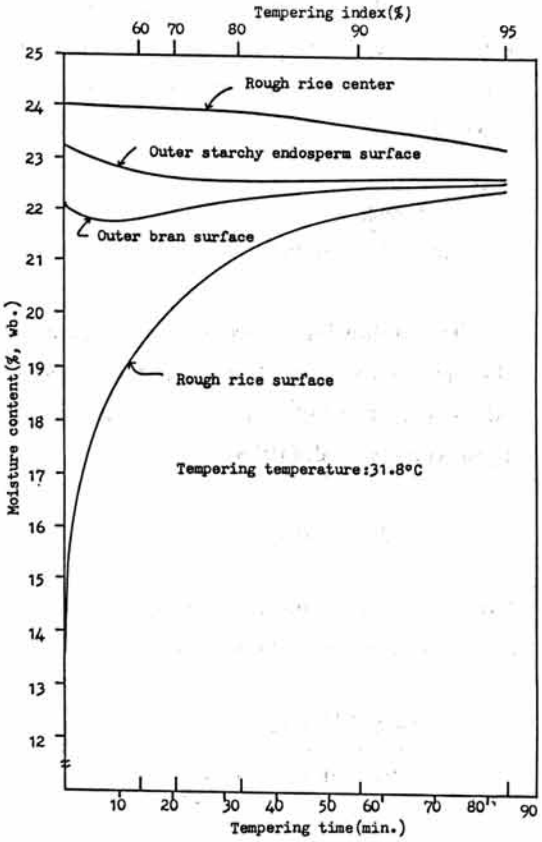

Fig. 3. Changes in moisture content during tempering after 20-min drying with 50°C-drying air.

Table 4. Moisture distribution within a kernel at various tempering levels after 5th tempering pass. (50°C-drying air and 20-min resident time for each drying pass) (%, Wb.)

Tempering index (%)	Total tempering time (hr)	Rough rice center	Outer starch endosperm	Outer bran surface	Rough rice surface	Maximum moisture difference
After the first drying pass		24.00	23.23	22.10	13.59	10.41
60	1.25	20.09	17.01	16.07	14.40	5.69
80	2.65	18.91	16.89	16.45	15.72	3.19
90	4.25	18.21	16.88	16.65	16.28	1.93
95	6.15	17.71	16.89	16.78	16.60	1.11

B. Tempering time prediction

Tempering period per pass for a a given tempering index was slightly decreased as drying progressed and resident times per pass increased. The differences in tempering period between passes, and between different resident times for a given tempering index were small to be negligible.

Average tempering period per pass required for a given a tempering levels (index) at various drying air temperatures were presented in Fig. 4. A non-linear, least square regression program was used to derive the tempering time prediction equation as a function of tempering index (decimal) and drying air temperature (°C). The equation was

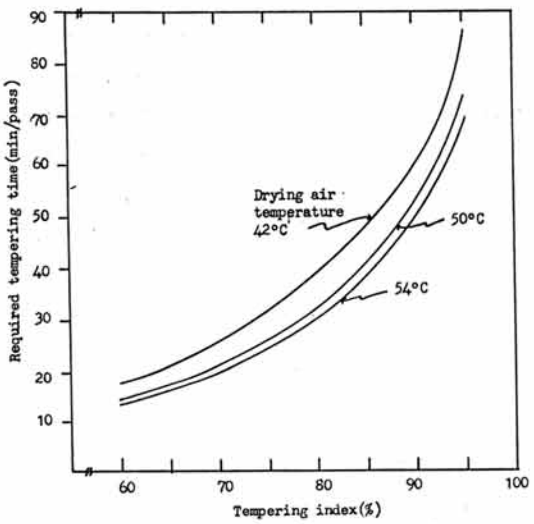

Fig. 4. Required tempering time versus tempering index for various drying air temperatures.

$$t_p = (2.59-0.0305T)\,\mathrm{EXP}\,(3.875I_c + 0.0108T\cdot I_c) \tag{25}$$

C. Drying rate, grain temperature and rice quality

Drying rate based on total drying time (total resident time + total tempering time) and maximum average grain temperatures after dried to 16% wb. versus tempering levels for three drying air temperatures were presented in Fig. 5 to Fig. 7, respectively.

Maximum average grain temperatures were reduced by decreasing resident time and increasing tempering time. Drying rate showed the same trend as that of maximum average grain temperatures.

Using the grain quality creteria specified earlier, 38°C and 1.5% wb./hr, the proper resident time and the minimum tempering level could be determined. In the case of 54°C-drying air, as shown in Fig. 6, only 15 min resident time and temperig index of more than 80% appeared to be adequate for maintaining maximum grain temperature less than 38°C and drying rate less than 1.5% wb./hr. Applying the same grain temperature limit and drying rate limit ranged from1.0% wb./hr to 1.5% wb./hr considering grain quality and dryer capacity to the case of 50°C and 42°C drying air, recommended resident and tempering times were determined as shown in Table 5.

Head rice yield ratios in Table 6 were the results simulated from Equation (24). Those were increased by reducing resident time, increasing tempering time and lowering drying air temperature. When resident time reduced from 35 min to 15 min, head rice yield ratio increased by 0.6% to 1.3% point. Increasing of tempering index from 60% to 95% resulted in about 0.2% to 0.7% point increase in head rice yield ratio. Head rice yield ratios, as shown in Table 5, were more than 98.6% when maximum average grain temperature and drying rate were less than 38°C and 1.5% wb./hr respectively.

In the Equation(24) predicting the head rice yield ratio, tempering effect was not included. Therefore, a new equation consider-

Table 5. Resident and tempering times recommended for the limits of maximum drying rate ranged from 1.0 to 1.5%, wb./hr and 38°C-maximum average grain temperature.

Drying air temperature (°C)	Resident time per pass (min.)	Tempering index (%)	Tempring time (min.)	Head rice yield ratio (%)
54	15	85~93	42~60	greater than 98.6
50	15	78~90	33~55	99.6
	20	86~95	44~71	98.6
42	15	60~77	18~37	99.2
	20	67~85	24~51	98.9
	30	80~95	41~80	98.8
	35	82~95	45~80	98.7

Table 6. Simulation results of head rice yield ratio (%)

Resident time (min.)	Tempering index (%)	Drying air temperature (°C)		
		42	50	54
35	60~95	98.5 ~ 98.8	97.7 ~ 98.1	97.2 ~ 97.4
30	60~95	98.6 ~ 98.9	97.9 ~ 98.2	97.4 ~ 97.9
20	60~95	99.8 ~ 99.2	98.3 ~ 98.7	97.7 ~ 98.4
15	60~95	99.2 ~ 99.4	98.5 ~ 99.0	98.2 ~ 98.7

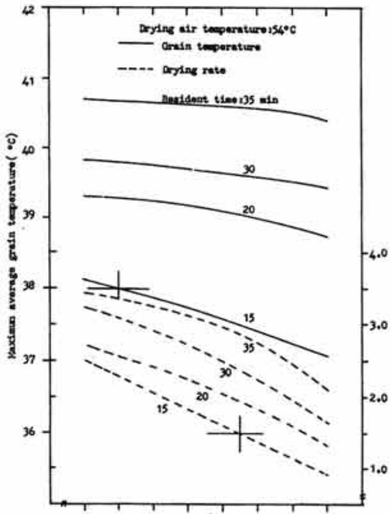

Fig. 5. Effect of tempering and resident time on maximum average grain temperature and drying rate.

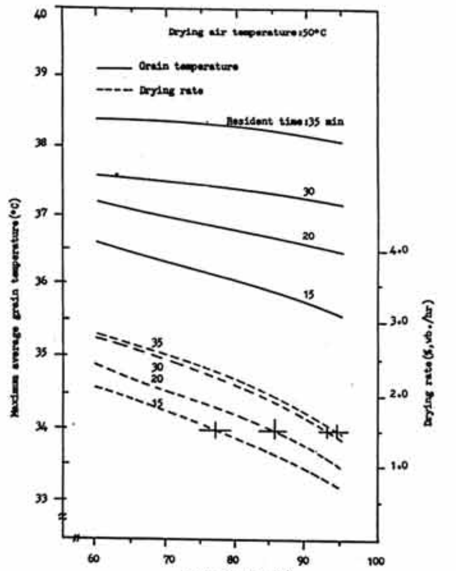

Fig. 6. Effect of tempering and resident time on maximum average grain temperature and drying rate.

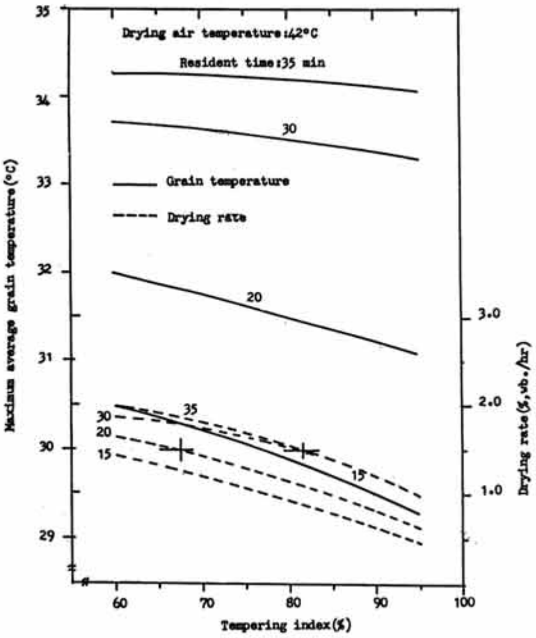

Fig. 7. Effect of tempering and resident time on maximum average grain temperature and drying rate.

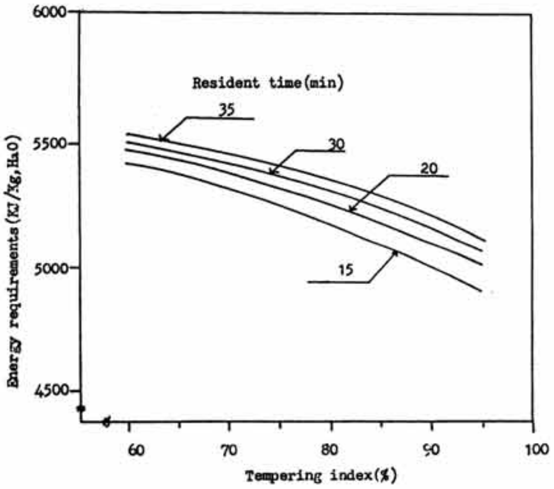

Fig. 8. Tempering effect on energy consumption required for drying to 16%, wb. with 50°C-drying air for various resident times.

ing tempering effect needs to be developed for evaluating head rice yield during multipass drying.

D. Energy requirements

Energy requirements predicted at 50°C drying air temperature were presented in Fig. 8. An increase in resident time increased energy requirements. An increase in tempering index resulted in decrease in energy requirements. For example, by increasing resident time from 15 min to 35 min for 90% tempering index, energy requirement for evaporating one kg of water was increased from 4900 kJ to 5200 kJ (6% increase). Increase in tempering level from 60% to 95% for 15 min resident time resulted in decrease in energy requirement from 5400 kJ to 4900 kJ (9% decrease).

VI. Conclusions

1. A simulation model for continuous flow rice drying based on liquid diffusion within a rice kernel which was assumed three concentric sphere composed of starch endosperm, bran ad hull was modified. The results indicated that this model was useful for the performance analysis of a continuous flow rice dryer.
2. Increasing tempering level between drying passes led to an increase in resident time drying rate and to a decrease in moisture gradient within a rice kernel. Tempering periods between passes were mainly affected by drying air temperature.
3. Maximum average grain temperature and drying rate for total drying time were reduced by decreasing resident time and by increasing tempering period.
4. To meet constraints for grain quality, maximum average grain temperature of 38°C and maximum drying rate of 1.5% wb./hr, the shorter resident time and the

longer tempering period were required as the drying air temperature became higher..

5. A set of resident and tempering periods recommended for practical use were presented considering the constraints for rice quality.
6. Energy requirements were reduced as resident time decreased and tempering period increased.

List of symbols

a = specific rice surface area (m^2/m^3)
c_a = specific heat of dry air (kJ/kg K)
c_p = specific heat of rice (kJ/kg K)
c_v = specific heat of water vapor (kJ/kg K)
c_w = specific heat of liquid water (kJ/kg K)
D_1 = Starch endosperm diffusivity (m^2/hr)
D_2 = Bran diffusivity (m^2/hr)
D_3 = rough rice diffusivity (m^2/hr)
E_a = heat energy requirements for removing 1 kg water from rice (kJ/kg H_2O)
E_f = fan energy requirements for removing 1 kg water from rice (kJ/kg H_2O)
G_a = air flow rate (dry air, kg/hr m^2)
G_p = grain flow rate (dry grain, kg/hr m^2)
h = convective heat transfer coefficient (kJ/m^2 K hr)
H = Humidity ratio (kg H_2O/kg dry air)
h_{fg} = latent heat of vaporization of water in rice (kJ/kg H_2O)
HR = Head rice yield ratio (actual head yield/initial head yield, decimal)
I_c = tempering index (decimal)
K = drying constant (hr^{-1})
ℓ = spatial node located at the outer edge of the rough rice kernel
M = local moisture content within a kernel (decimal, db.)
$\overline{M}$ = average moisture content for a kernel (decimal, db.)
M_e = equlibrium moisture content (decimal, db.)
M_o = initial moisture content (decimal, db.)
M_f = average final moisture content for bed-depth (decimal, db.)
$MR = \dfrac{\overline{M} - M_e}{M_o - M_e}$ = moisture ratio
ΔP = pressure drop (Pa)
Q_a = air flow rate (m^3/m^2, min)
r = variable radius (m)
R_1 = radius of white rice (m)
R_2 = radius of brown rice (m)
R_3 = radius of rough rice (m)

RH = relative humidity (decimal)
t = time (hr)
t_p = tempering time per pass (min.)
t_d = drying time (hr)
T = drying air temperature ($^{\circ}$C)
T_a = absolute temperature (K)
T_{amb} = ambient air tpmperature ($^{\circ}$C)
T_{in} = drying air temperature at inlet ($^{\circ}$C)
V_p = grain velocity (m/hr)
x = bed-depth coordinate (m)
X_c = bed-depth (m)
y = bed-height coordinate (m)
ρ = bulk density of dry rice (kg/m^3)
θ = grain temperature ($^{\circ}$C)
θ_a = absolute grain temperature (K)

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