稻穀間歇乾燥新薄層公式

陳貽倫

國立臺灣大學農業機械工程學系教授

摘 要

以國產粳稻作稻穀薄層間歇乾燥試驗，可變之乾燥參數及其範圍為：通風溫度自 35 至 60℃；通風風速自 15 至 25cm/s；每循環之乾燥時間自 5 至 15 分鐘；每循環之均化時間自 40 至 120 分鐘。

設每一處理之乾燥曲線皆遵照指數模式 $MR = A \cdot \exp(-kt)$、將每一處理之數據用迴歸法適配 (fit) 於該模式後、可得一組 A, k 值，在四個乾燥參數不同位階 (level) 組合之不同乾燥條件下，共獲 162 組 A, k 值，經第二次迴歸處理，分別得 A, k 二值之推算式 (Predictors)，此二推算式中之 A, k 值皆為上述四參數之函數，其相關性之決定係數分別為 0.674 和 0.913。

關鍵詞： 稻穀，薄層，間歇乾燥

A NEW THIN-LAYER EQUATION FOR INTERMITTENT DRYING OF ROUGH RICE

Yi-Luen Chen

Professor, Department of Agricultural Machinery Engineering, National Taiwan University

ABSTRACT

Intermittent drying experiment using paddy rice of medium grain were carried out with drying temperatures ranging from 35 to 60℃, drying air velocities from 15 to 25 cm/s, drying phase duration from 5 to 15 minutes, and tempering phase duration of 40 to 120 minutes as drying variables.

Each treatment of drying was assumed to take the commonly used exponential drying model of $MR = A \cdot \exp(-kt)$. A pair of A, k values were derived through a first-step regression by fitting the drying data into the model. One hundred and sixty-two pairs of A, k values were thus derived and fitted, with their corresponding levels of drying variables, into a pair of multivariate predictors for predicting A and k. These two predictors were found both to be functions of the above-mentioned four drying parameters. Their determination coefficients of correlation were 0.674 and 0.913, respectively.

Keywords: Rough rice, Thin layer, Intermittent drying

INTRODUCTION

A thin-layer equation defines the drying curve of a farm product, such as paddy rice, under a definite set of drying parameters. It determines the moisture content, or the drying rate, or the change of drying rate of the product at any particular time during the drying process.

Different thin-layer drying models for paddy rice have been developed by different researchers through the years. Most of them take one of the following forms:

1. $MR = A \cdot \exp(-kt)$ or $\ln(MR) = A - kt$
2. $MR = \exp(-At^B)$
3. $MR = A + Bt + Ct^2$
4. $MR = A \cdot \exp(Bt) + C\exp(Dt)$
5. $t = A \cdot \ln(MR) + B \cdot [\ln(MR)]^2$

where MR represents moisture ratio of the grain, t is drying time, and A, B, C, D, k are constants which are functions of the temperature and humidity of the drying air.

Form 1 is an equation analogous to Newton's law of cooling, and is the most commonly used. Henderson and Perry (1976) showed that form 1 describes rice drying very well except for the first two hours. Yamazawa et al.(1971), Kameoka (1988) and Chen(1996a) fitted their experiment data into form 1 as well. They also found that the drying behavior for the initial period of rice drying was different from that of the later drying, therefore, the drying data at the initial period deviate from the drying curve defined by the model.

Form 1 has a good feature that it appears as a straight line on semi-log coordinates, with intercept A and slope $-k$. The intercept A (called the "shape factor" in some literature) is less than one and explains the deviation of the estimated values from the experimental ones for the initial drying stage.

Form 2 does not have the intercept problem, but the drying rate is no longer a straight line on semi-log coordinates. Form 3 was developed by Wang and Singh(1978) to facilitate numerical techniques. Forms 1, 2 and 5 are semi-theoretical, forms 3 and 4 are empirical.

A two-compartment model for paddy rice was proposed by Sharma et al.(1982) on the basis that the rice grain consists of two distinct components as the hull, bran and starch endorsperm. Chen and Tsao (1994) used their experiment data to fit the first four of the above-listed models and found the two-compartment model to be the best fit.

In batch re-circulating rice dryers, which are prevailing in numbers in rice-producing Asian countries, the grain is dried in an intermittent pattern. The grain is first dried for about 5 to 15 minutes before it is passed through the drying zone of the dryer, and then the grain goes to the tempering zone to be tempered for about 40 to 120 minutes. The drying-and-tempering cycle is repeated as the grain re-circulates in the dryer until the grain reaches the desired moisture content.

Using drying air temperatures ranging from 35 to 60℃, absolute humidities from 17 to 31 g/kg of dry air, and a drying air velocity at 21 cm/s, Chen(1996a) performed a set of thin-layer intermittent drying experiments with medium grain rice of the Japonica variety. Based on these data, he developed a thin-layer equation as follows.

$$MR = A \cdot \exp(-kt)$$

where

$A = 1.026337 - 0.00453 \cdot T + 0.002551 \cdot H$

$-k = 0.001496 - 0.00026 \cdot T + 0.000008 \cdot H$

MR: moisture ratio

t: accumulated drying time, min

T: drying air temperature, ℃

H: drying air absolute humidity, g/kg

He also applied it to rice drying simulation and obtained an excellent result (Chen,1996b). Since both the drying time and the tempering time intervals were fixed to 10 and 50 minutes respectively, its application is limited.

While some researchers (Wang and Singh, 1978; Agrawal and Singh, 1977; Islam and Jindal,1981; and Chen, 1996a etc.) included drying air humidity in their thin-layer equations, Others (Sharma et al.,1982; Chuma et al.,1969; Yamazawa ,1971; Otsuka et al.,1975; Bucklin and Wratten,1978; and Kameoka,1988) did not.

Using air relative humidities from 3 to 60%, air velocities from 2.5 to 50 cm/s, and air temperature from 35℃ to 95℃, Bucklin and Wratten (1978) ran a series of drying tests, and concluded that the drying constant for single layers of rough rice was independent of drying air velocity and relative humidity of the drying air over the tested range. They suggested that the effects of drying air velocity and humidity be neglected in further work to establish a thin-layer drying equation for rough rice.

According to Chen's (1996a) equation above, the value of the drying constant k varies only a few percentage points if the humidity of the drying air changes from 10 to 30 g/kg of dry air (20 to 60% RH) at a drying temperature of 40℃.

The objective of this study was to develop a better thin-layer equation for the intermittent drying of rice. The equation includes and reflects both the effect of the length of time intervals of the drying and the tempering phases of the recirculating drying. The effect of drying air velocity through the grain is also included.

EQUIPMENT AND PROCEDURE

The first crop of the Japonica variety, Medium grain rice, with a moisture content of 35 – 40% d.b., produced in Central Taiwan in 1996, was used.

The drying experiment were carried out in a sample dryer, which has 12 cylindrical drying cells (15.6 cm inside diameter and a 16 cm height). Each cell can be removed from the dryer body to be weighed or to load or unload its content. The dryer was fully described in author's previous paper (Chen,1996a).

The grain was spread on the screen of the drying cells to be dried. The rice bed had a thickness of 2 to 3 grains. The drying air for each drying cell was regulated to desired temperature. The drying air flow rates at all 12 cells were the same for one particular run of the experiment, and could be adjusted by means of an AC transformer, which determined the voltage to the power motor.

A humidifier was used to keep the absolute humidity of the drying air a little higher than the ambient and then to keep it steady throughout the experiment.

EXPERIMENT DESIGN

Sample weight: 50 g

Air velocity: 15, 20, 25 cm/s

Time interval for each drying phase: 5, 10, 15 min

Time interval for each tempering phase: 40, 80, 120 min

Drying air temperature: 35, 40, 45, 50, 55, 60℃

Drying air humidity: 16 g/kg of dry air

Number of total treatment: $3 \times 3 \times 3 \times 6 = 162$

Replications: 2

PROCEDURE

Newly-harvested paddy rice was stored in a storage at 5℃. About one kilo-gram of the paddy was taken from the storage to warm up to room temperature before an experiment was run. The paddy was divided by a Seedburo grain divider into 16 equal lots. Samples of 50-grams of grain were taken from each of 12 lots out of the 16 lots and sealed in 12 glass bottles.

Some grain of the remaining lots was used to determine the initial moisture content by the Oven Method. Dry basis moisture content was used in this study.

Drying air velocity and temperatures for each drying cell were adjusted to the desired values. The grain was poured from the bottles into the drying cells and spread evenly on the screens before starting drying.

Cells were removed from the dryer stand, weighed and grain samples sealed in glass bottles after the drying phase was over. The grain samples, tempered in the bottles for a set time till the next drying phase. The drying and tempering cycles were repeated until the grain reached the desired moisture content.

METHOD OF DATA ANALYSIS

An assumption was made at the beginning that the relation between the moisture ratio of the grain during drying and the accumulated drying time of each drying treatment was according to an exponential model as form 1 mentioned previously. Regression analyses were made for each drying treatment. Shape factor (A) values, drying constants (k), and coefficients of determination (R^2) were calculated.

The values of A and k were anticipated to be affected by the drying air temperature, the drying air velocity, and both the duration of drying and tempering phases of the drying cycle. Multivariate predictors were proposed for predicting both the factor A and the drying constant k as follows,

$$\begin{aligned} A &= A_0 + A_1V + A_2X + A_3Y + A_4T \\ &\quad + A_5XT + A_6YT + A_7T^2 \qquad (1) \\ -k &= k_0 + k_1V + k_2X + k_3Y + k_4T \\ &\quad + k_5XT + k_6X^2 + k_7XY \qquad (2) \end{aligned}$$

where V, X, Y, T stand for drying air velocity, duration of drying phase, duration of tempering phase, and drying air temperature, respectively. A_0, A_1, $\ldots A_7$, and k_0, k_1, $\ldots k_7$ are the constants and coefficients to be determined by a second-step regression , using the individual A and k data acquired by previous first-step regression, from each drying curve of all treatments as observed.

RESULTS AND DISCUSSION

Figure 1 shows a set of drying curves at different temperatures which were resulted from a portion of the experiments, in which the drying period and the tempering period were set to 5 minutes and 80 minutes, respectively, and air velocity at 20 cm/s. If the same set of data are presented on semi-log coordinates, they are nearly linear. Fitting drying data from each treatment into the linear model of form 1 and using the regression technique, the intercept A, the slope k and the coefficient of determination of each of all drying curves were individually or independently-derived. A representative sample of these values were listed in columns (5), (6) and (7) of Table 1.

The high R^2 values for all the treatments showed that the form 1 model was adequate to simulate drying curves resulting from intermittent drying.

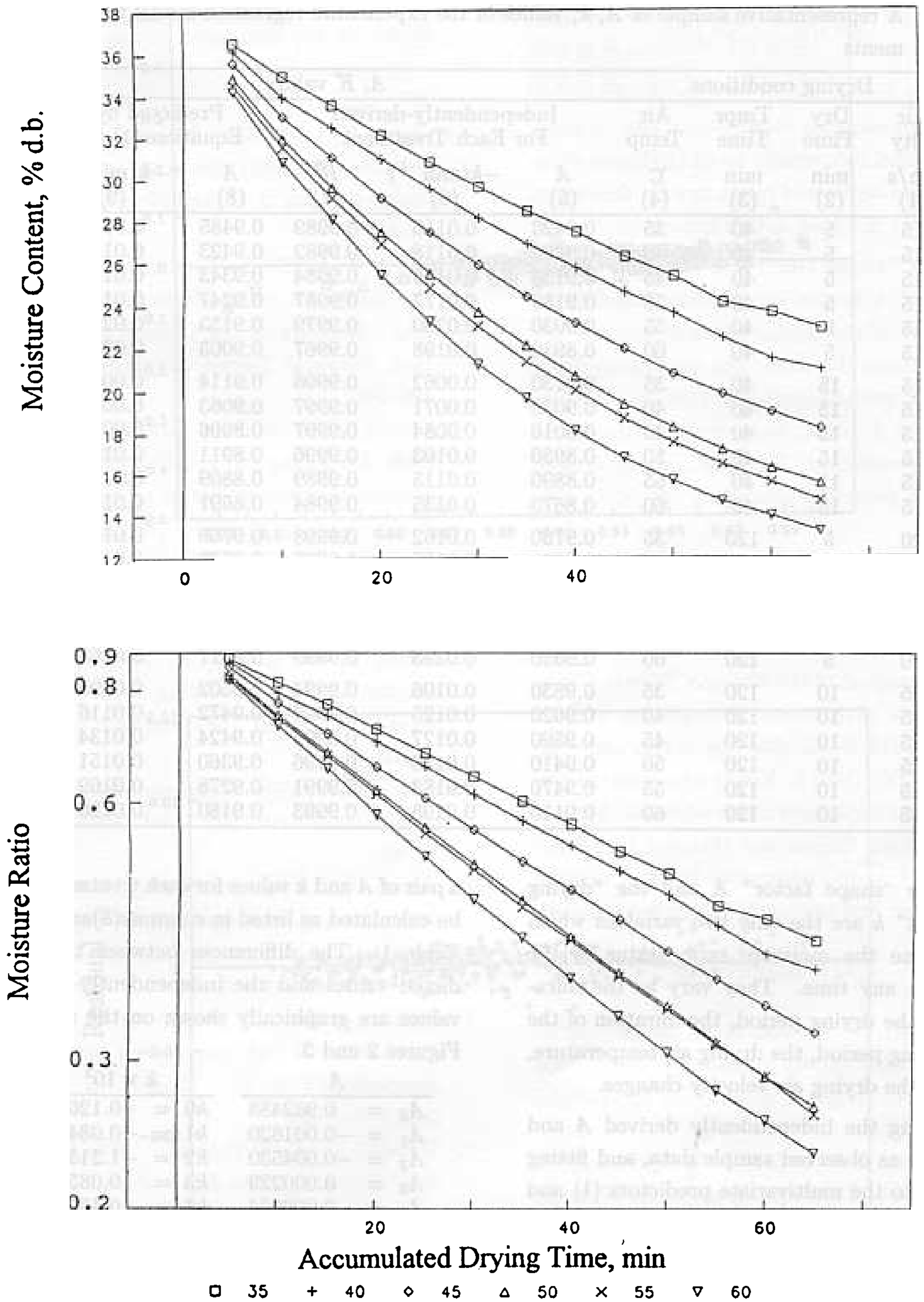

Fig. 1 Drying Curves at Different Temperatures

Table A representative sample of A, k, values of the exponential regression model for all treatments

Drying conditions				A, K values				
Air Vlty	Dry Time	Tmpr Time	Air Temp	Independently-derived For Each Treatment			Predicted by Equations(1),(2)	
cm/s (1)	min (2)	min (3)	℃ (4)	A (5)	$-k(\text{min}^{-1})$ (6)	R^2 (7)	A (8)	$-k(\text{min}^{-1}$ (9)
15	5	40	35	0.9420	0.0110	0.9989	0.9485	0.0116
15	5	40	40	0.9320	0.0118	0.9982	0.9423	0.0137
15	5	40	45	0.9130	0.0155	0.9984	0.9343	0.0158
15	5	40	50	0.9180	0.0177	0.9987	0.9247	0.0179
15	5	40	55	0.9030	0.0200	0.9979	0.9133	0.0200
15	5	40	60	0.8930	0.0198	0.9967	0.9003	0.0221
15	15	40	35	0.9130	0.0062	0.9996	0.9114	0.0067
15	15	40	40	0.9030	0.0071	0.9997	0.9063	0.0080
15	15	40	45	0.9010	0.0084	0.9997	0.8996	0.0094
15	15	40	50	0.8930	0.0103	0.9996	0.8911	0.0108
15	15	40	55	0.8890	0.0115	0.9989	0.8809	0.0122
15	15	40	60	0.8670	0.0135	0.9984	0.8691	0.0136
20	5	120	35	0.9760	0.0162	0.9998	0.9769	0.0162
20	5	120	40	0.9720	0.0185	1.0000	0.9733	0.0183
20	5	120	45	0.9610	0.0208	0.9999	0.9680	0.0204
20	5	120	50	0.9700	0.0250	0.9999	0.9609	0.0225
20	5	120	55	0.9660	0.0270	0.9999	0.9522	0.0247
20	5	120	60	0.9550	0.0293	0.9999	0.9417	0.0268
25	10	120	35	0.9830	0.0106	0.9994	0.9502	0.0099
25	10	120	40	0.9620	0.0125	0.9994	0.9472	0.0116
25	10	120	45	0.9590	0.0127	0.9996	0.9424	0.0134
25	10	120	50	0.9410	0.0136	0.9996	0.9360	0.0151
25	10	120	55	0.9470	0.0153	0.9991	0.9278	0.0169
25	10	120	60	0.9110	0.0198	0.9993	0.9180	0.0186

The "shape factor" A and the "drying constant" k are the only two variables which determine the moisture ratio status of the grain at any time. They vary as the duration of the drying period, the duration of the tempering period, the drying air temperature, and as the drying air velocity changes.

Using the independently derived A and k values as observed sample data, and fitting them into the multivariate predictors (1) and (2), the coefficients on the right side terms of the equations were found, by applying the second-step regression, as listed below.

Using equations (1) and (2) and with all the constants or coefficients listed on the right, a pair of A and k values for each treatment can be calculated as listed in columns(8)and(9) of Table 1. The differences between the predicted values and the independently-derived values are graphically shown on the residual Figures 2 and 3.

A	$k \times 10^3$
A_0 = 0.982488	$k0$ = −0.126990
A_1 = -0.001620	$k1$ = −0.084920
A_2 = -0.004530	$k2$ = −1.213000
A_3 = 0.000229	$k3$ = 0.085187
A_4 = 0.000924	$k4$ = 0.493214
A_5 = 0.000023	$k5$ = −0.014300
A_6 = 0.000006	$k6$ = 0.069789
A_7 = -0.000030	$k7$ = −0.004340
Std Err of A Est 0.018971	Std Err of k Est 0.00156
$R^2 = 0.674$	$R^2 = 0.913$

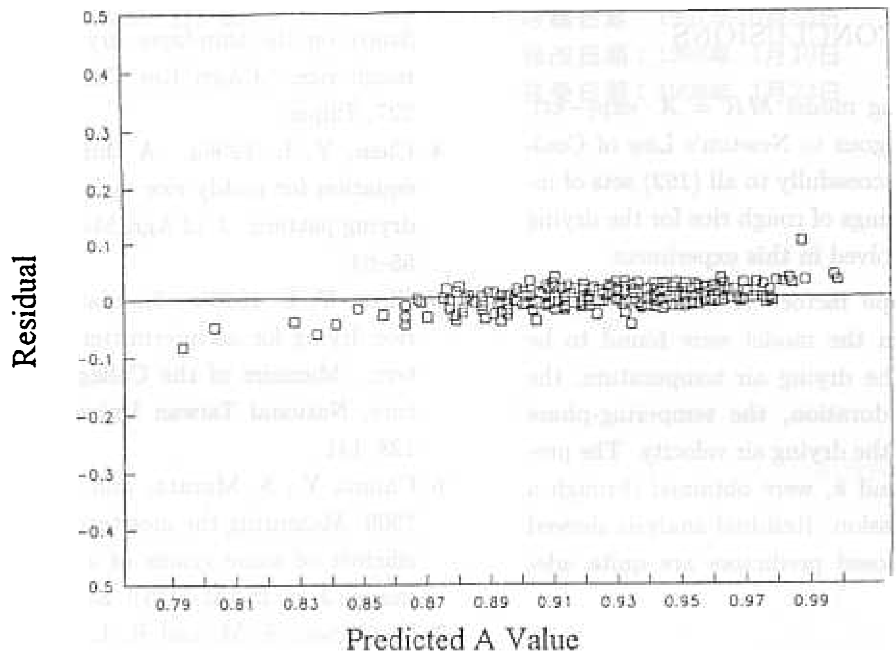

Fig. 2 Residual for the Predictor of A

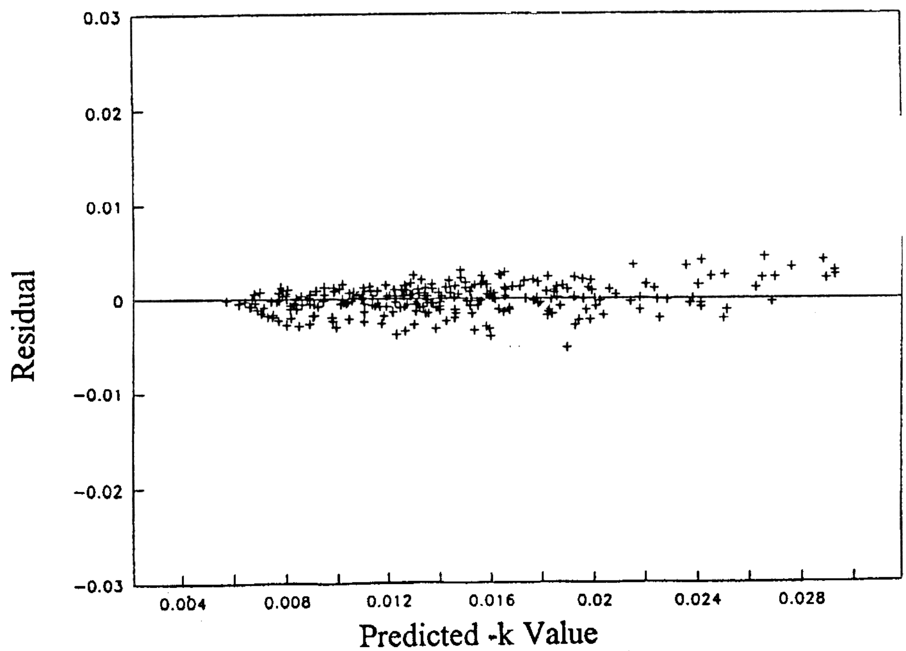

Fig. 3 Residual for the Predictor of $-k$

CONCLUSIONS

The drying model $MR = A \cdot \exp(-kt)$, which is analogous to Newton's Law of Cooling, applied successfully to all (162) sets of intermittent dryings of rough rice for the drying conditions involved in this experiment.

The "shape factor" A and the "drying constant" k in the model were found to be functions of the drying air temperature, the drying-phase duration, the tempering-phase duration, and the drying air velocity. The predictors of A and k, were obtained through a two-step regression. Residual analysis showed that the proposed predictors are quite adequate.

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REFERENCES

1. Agrawal, Y. C. and R. P. Singh. 1977. Thin-layer drying studies for short-grain rice. ASAE paper No.77-3531 St. Joseph, MI. 49085.
2. Bucklin, R.A. and F.T. Wratten. 1978. Variation of the drying constants of rough rice with velocity, relative humidity, and temperature of the drying air. A paper for presentation at the 1979 Southwest Region Meeting, ASAE, Hot Spring, Arkansas.
3. Chen, C. C., and C. T. Tsao. 1994. Study on the thin-layer drying model for rough rice. J.Agri Res. China 43(2):208–227, Taipei.
4. Chen, Y. L. 1996a. A thin-layer drying equation for paddy rice in an intermittent drying pattern. J. of Agri.Machinery. 5(1): 55–64.
5. Chen, Y. L. 1996b. Simulation of paddy rice drying for an intermittent drying pattern. Memoirs of the College of Agriculture, National Taiwan University. 36(2): 128–141.
6. Chuma Y., S. Murata, and M. Iwamoto. 1969. Measuring the moisture diffusion coefficient of some grains of an amomalous shape. J. of JSAM 31(3): 250–255.
7. Henderson, S. M. and R. L. Perry. 1976. Agricultural process engineering. 3rd ed., pp.310–316. Westport, Conn.: AVI Co..
8. Islam, M. N. and V. K. Jindal. 1981. Simulation of paddy drying under tropical conditions. AMA 1981 Summer p.37–41. Japan.
9. Kameoka, T. 1988. Thin layer drying characteristics of rough rice. J. of JSAM 50(4): 57–65.
10. Otsuka K., S. Murata, and Y. Chuma. 1975. An empirical equation for thin layer drying of rough rice with heated air. J. of JSAM 37(3): 331–338.
11. Sharma, A. D., O. R. Kunze and H. D. Tolley. 1982. Rough rice drying as a two-compartment model. Trans. of ASAE 25(1): 221–224.
12. Wang C. Y. and R. P. Singh. 1978. A thin-layer drying equation for rough rice. ASAE paper No.78-3001 St.Joseph, MI 49085.
13. Yamazawa S., S. Yoshizaki, T. Maekawa, and K. Sonobe. 1971. Study on drying of agricultural products (II)–Characteristics on moisture transfer of the grain drying.

J.of JSAM 33(3): 279–287.

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