ENERGY MODEL OF GRAIN DRYING SYSTEM

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ABSTRACT

Energy analysis in grain drying was conducted by employing a mathematical model which comprises various submodels, i.e., prediction of temperature rise by shaft work for driving fan, drying rate, air properties, dry matter loss and grain bulk shrinkage. The model predicts the drying rate with an acceptable degree of accuracy, particularly for low air flow rate and temperature. Prediction of energy consumption is less accurate; nevertheless, it gives error of less than 20%. Under hot and humid climates, it is recommended to dry paddy with low air flow rate and near-ambient air to minimize energy consumption and moisture gradient in the grain bed and to obtain high percentage of head yield. It is also recommended to dry paddy in storage bins. If ambient air is humid, it may be heated with a temperature rise of 5°C.

INTRODUCTION

Mathematical simulation of grain drying was widely studied in the past. Some examples of these are non-equilibrium model¹, near-equilibrium model² and logarithmic model^{3,4}. The accuracy of the model and the difficulty in obtaining its solution is in order of the above-mentioned models.

Analysis of drying processes in isolation is not sufficient for the energy analysis of grain drying systems. Shaft energy for driving fan and its transformation into heat, heat for heating air, and in some cases heat generation in the system by the respiration of microorganism and grain should be considered in the analysis. The objectives of this paper are as follows:

1. To develop a mathematical model which describes energy consumption patterns in grain drying by various strategies.
2. To test the accuracy of the model by comparing with experimental work.
3. To recommend appropriate drying strategies. Paddy is selected as a case study.

PROCEDURES

1. Development of Mathematical Model

To achieve the above objectives, a mathematical model called “Drying Paddy” was developed. It comprises various submodels to predict the temperature rise at fan, drying rate, moist air properties, dry matter loss, and grain bulk shrinkage.

a. Temperature rise by shaft energy

Temperature rise of air while flowing across a fan can be determined by applying the First Law of Thermodynamics for steady-state-flow process. It is written as

$$Dh = Q + W_s \quad \text{.....(1)}$$

where Dh is the enthalpy change of the air while flowing across the fan, Q is heat exchange between the fan and surrounding and may be neglected, and W_s is shaft power for driving fan.

Substituting Dh by assuming that the air is an ideal gas and only the portion of dry air is accounted, and W_s into Eqn.(1), yields

$$\begin{aligned} mc_a DT_f &= mP/D_a E_f \\ \text{or } DT_f &= P/D_a E_f c_a \quad \text{.....(2)} \end{aligned}$$

where m = mass flow rate of air, kg/s
 c_a = specific heat of air at constant pressure, J/kg°C
 D_a = air density, kg/m³
 P = total pressure, Pa
 DT_f = temperature rise across the fan, °C
 E_f = fan efficiency, decimal

The temperature rise of the air obtained by Eqn.(2) is more accurate compared to the assumption that temperature rise is 1°C as found in some literatures^{5,6}. This is important for the prediction of energy consumption in grain drying system particularly for drying with near-ambient air where main energy input is at the fan.

The pressure drop across the grain bed and the air duct is determined by Eqn. (3).

$$P = (SF) (aV^b) \quad \text{.....(3)}$$

where V is the apparent air velocity through the grain bed (m/min), a and b are determined from Shedd's data⁷ for rough rice and are equal to 36.78 and 1.17, respectively. SF is a safety factor to ensure proper selection of fan. This includes the effect of pressure drop in the air duct, grain bed and other uncertainties. In this paper SF is 1.5 if not specified and fan efficiency is

assumed to be 0.6.

b. Drying model

The drying model developed herein is somewhat similar to the original near-equilibrium model². However, modification in some equations and steps of calculation were modified. At a certain grain layer and a small interval of drying time, it is assumed that the air and grain are in thermal equilibrium (thermal equilibrium is in order of minutes while moisture equilibrium is in order of days). The equation is derived from the First Law of Thermodynamics assuming heat loss is very small. Thus the sum of changes of the internal energy of a control volume and the enthalpy of flowing stream is equal to zero.

$$c_a T_o + (2502 + c_v T_o) W_o + R c_{pw} T P_o = c_a T_{bd} + (2502 + c_v T_{bd}) W_{bd} + R c_{pw} T_{bd} \quad \text{.....(4)}$$

where T , W , and TP are air temperature, absolute humidity, and grain temperature, respectively. The subscripts o and bd refer to the conditions before and after thermal equilibrium. It is noted that W_o is equal to W_{bd} . The symbols c_a and c_{pw} are the specific heat of air and wet grain. R is the ratio of the dry grain mass in the layer to the dry air mass flowing through that layer in the considered time interval.

When T_{bd} is determined from Eqn. (4), air relative humidity is then checked. If it is higher than 1, T_{bd} and W_{bd} are replaced by T_o and W_o and moisture condensation is simulated using Eqn. (5) similar to Eqn. (4).

$$c_a T_o + (2502 + c_v T_o) W_o + R c_{pw} T_o = c_a T_{bd} + (2502 + c_v T_{bd}) W_{bd} + R c_{pw} T_{bd} \quad \text{.....(5)}$$

T_{bd} and W_{bd} can be solved by assuming that the relative humidity after simulation is equal to 1. Then the condensed moisture is absorbed by the grain. It is calculated by the equation of mass conservation.

$$M_{bd} - M_o = (W_o - W_{bd}) / R \quad \text{.....(6)}$$

where M_{bd} and M_o are the moisture content (decimal dry basis) of grain after and before condensation, respectively.

The next step is to calculate the equilibrium moisture content. The following equation⁸ was used.

$$M_{eq} = 100 \left[\ln(1 - RH_{bd}) / \{-7.87 \times 10^{-6} (1.8 T_{bd} + 491.7) \} \right]^{1/2.088} \quad \text{.....(7)}$$

where M_{eq} is equilibrium moisture content and T_{bd} and RH_{bd} are air temperature and relative humidity after thermal equilibrium, respectively.

To calculate the drying rate of thin layer, the following empirical equation⁹ was used. It is written as

$$(M - M_{eq})/(M_{in} - M_{eq}) = \exp(-xt^y) \quad \text{.....(8)}$$

$$\text{where } x = 0.02958 - 0.44565(RH) + 0.01215(T)$$

$$y = 0.13365 + 1.93653(RH) - 1.77431(RH)^2 + 0.009468(T)$$

$$T = \text{drying air temperature, } ^\circ\text{C}$$

$$RH = \text{air relative humidity, decimal}$$

$$M = \text{moisture content, decimal dry basis}$$

$$M_{in} = \text{initial moisture content, decimal dry basis}$$

To calculate for both drying and rewetting processes, eqn.(8) is differentiated with respect to time and the differentials are replaced by the finite differences. It is written as

$$M_f = (M_{bd} - cM_{eq})/(1-c) \quad \text{.....(9)}$$

where M_f is grain moisture content after drying

$$\text{and } c = -xyDt^{(y-1)}$$

where Dt is the time interval for simulation and t is the drying time.

Air properties after drying are calculated by the equations of mass conservation and energy conservation.

$$W_f - W_{bd} = (M_{bd} - M_f)R \quad \text{.....(10)}$$

$$c_a T_{bd} + (2502 + c_v T_{bd})W_{bd} + R c_{pw} T_{bd} = c_a T_f + (2502 + c_v T_f)W_f + R c_{pw} T_f \quad \text{.....(11)}$$

where W_f and T_f are the absolute humidity and temperature of air after drying or rewetting. Air relative humidity is then checked. If it is higher than 1, T_f , W_f and M_f are replaced by T_o , W_o and M_o and then moisture condensation is simulated.

$$c_a T_o + (2502 + c_v T_o)W_o + R c_{pw} T_o = c_a T_f + (2502 + c_v T_f)W_f + R c_{pw} T_f \quad \text{.....(12)}$$

$$\text{and } M_f - M_o = (W_o - W_f)/R \quad \text{.....(13)}$$

At this stage drying and rewetting simulation is completed for a considered grain layer. The exhaust air is assumed to be the inlet air condition of the next layer. The calculation continues until the last layer and then the time step is advanced.

c. Moist air properties

The relationship of moist air properties was found by the use of psychrometric equations¹⁰.

d. Dry matter loss

Dry matter loss of rough rice in function of elapse time, moisture content and temperature of grain is as the following equation¹¹.

$$\text{DML} = 1 - \exp(-\text{TERM}) \quad \text{.....(14)}$$

$$\text{where TERM} = A(t/100)^C \exp[D(1.8T - 28)] \exp[E(M_w - 0.14)]$$

DML = dry matter loss, decimal

t = elapse time, h

T = temperature, °C

M_w = moisture content, decimal wet basis

for long grain A = 0.001889

C = 0.7101

D = 0.0274

E = 31.63

Due to the variation of moisture content and temperature of grain, equivalent time is used for the calculation of DML in Eqn. (14). Knowing the dry matter loss at the end of the previous time step, equivalent time for the beginning of the considered time step is determined by substituting the moisture content and grain temperature at the considered time step into Eqn. (14). The elapse time for the considered time step is then equal to the summation of equivalent time and time interval (Dt).

When dry matter loss occurs, heat is produced. The process is explained by Eqn. (15)

From Eqn. (15), 1% of dry matter loss/kg of dry matter produces 0.156 MJ of heat. If dry matter loss during drying is too high, heat from the respiration process will be significant compared with the main energy input. In this study, dry matter loss is limited to not higher than 0.5%. The heat from respiration is not included in the model. More study of the effect of heat of respiration on the drying rate was done^{12,13}.

e. Shrinkage

Shrinkage of grain bulk during drying is not important for the energy analysis. However, it is useful for predicting the volume required to store the grain after drying. An equation for predicting the shrinkage of the bulk of long grain rough rice was developed¹⁴. It is written as

$$v = 0.001997 + 0.0012M \quad \text{.....(16)}$$

where v is the volume per kg of dry matter, m^3/kg
 M is moisture content, decimal dry basis

Equation (16) is valid for the range of moisture content from 0.12 to 0.39 decimal dry basis.

f. Computer program

A computer program incorporating the above equations was written in BASIC language. Grain moisture content and temperature are the initial conditions and ambient air temperature and relative humidity are the input weather data. Air flow rate and the thickness of grain bed are selected and the temperature rise is then calculated. The air may be constantly heated at any desired temperature or may be heated during high relative humidity, i.e., inlet air relative humidity is controlled at any desired range. The fan may be continuously operated or operated only when the relative humidity is lower than the set value. Grain moisture content and temperature, dry matter loss, and shrinkage are then calculated for each layer. At the end of drying, total time, time of fan operation, power for fan, pressure drop, power for constant heating, power for maximum temperature rise by relative humidity control, energy for fan, energy for heater, temperature rise by fan, temperature rise by constant heating, and maximum temperature rise by relative humidity control are presented. The efficiencies of electrical motor and heater are assumed to be 0.9 and 1, respectively. The simulation flow chart is presented in Annex A.

2. Testing of Mathematical Model

The results from the mathematical model, which gives moisture content and energy consumption patterns, will be compared with the experimental results in Table 1.¹⁵ The experimental results show that drying with low air flow rate and near-ambient air tends to consume lower energy than the drying with high air flow rate. Due to the very slow drying rate at the end of drying of the test run number 9 (from 42 hours to 60 hours) compared to other test runs which have much higher drying rate at the end of drying, the values of grain moisture content and energy consumption at 42 hours are used instead of at 60 hours. The comparison among different test runs may then be more reasonably done.

TABLE 1
EXPERIMENTAL RESULTS OF PADDY DRYING*

Test runs no.	5	6	7	8	9	10	11
Strategies	1	1	3	2	4	5	5
Moisture content (% w.b.)							
Initial	18.29	15.17	18.73	20.63	18.26	19.25	19.25
Final, top	16.46	14.89	16.57	16.75	14.32	16.78	17.78
middle	14.50	14.35	13.72	14.04	13.54	12.65	13.60
bottom	11.20	13.39	12.30	11.78	13.06	9.82	10.66
average	14.05	14.21	14.20	14.19	13.62	12.97	13.91
Air flow rate (M ³ /min-m ³ of paddy)	2.27	2.27	2.17	2.21	15.49	15.40	15.40
Grain bed (m)	1.6	1.6	1.6	1.6	0.4	0.4	0.4
Ambient air							
temperature (°C)	27.7	29.4	29.3	29.4	29.8	27.7	27.4
relative humidity(%)	77.3	78.4	65.6	73.8	76.9	65.1	75.9
Average temperature rise (°C)	1.5	1.2	0.9	2.5	0.7	15.8	15.3
Drying time (h)	144	48	216	144	60	9	9
Net energy consumption (MJ/kg H ₂ O)							
Energy consumption (MJ/kg H ₂ O)							
- Final energy							
mechanical	1.42	2.03	1.11	0.86	3.13	0.32	0.36
heat	-	-	-	0.52	-	2.36	2.53
total	1.42	2.03	1.11	1.38	3.13	2.68	2.89
- Primary energy	3.69	5.27	2.88	2.77	8.14	3.19	3.47

*From Soponronnarit, S. and Chinsakoltanakorn, S. (1986)

Strategies nos. 1-3 : low air flow rate

- 1 - continuous ventilation with ambient air
- 2 - continuous ventilation with relative humidity less than 75%
- 3 - ventilation when relative humidity less than 75%

Strategies nos. 4-5 : high air flow rate

- 4 - continuous ventilation with ambient air
- 5 - continuous ventilation with hot air

During simulation, the value of SF in Eqn. (3) was varied so that the calculated temperature rise by fan was closed to the measured one. The effect of temperature rise by fan was studied. This was done by neglecting the temperature rise during computer simulation.

RESULTS AND DISCUSSION

1. Test of Drying Model

The developed drying model was tested for its accuracy of predicting drying rate and energy consumption compared to the experimental results of different drying conditions, i.e. several air flow rates, drying air temperatures and relative humidities.

Table 2 shows the comparison between the experimental and simulated final moisture content. The model could predict well when air flow rate and temperature were low (test runs nos. 5–8). The simulated drying rate tends to be slower than the experimental one. However, it is faster for drying with high air flow rate (test runs nos. 9–11), particularly at high temperature (test runs nos. 10–11), due to the assumption that thermal equilibrium between the grain and the air exists. It is approximately true when drying air temperature and flow rate are low. The simulated and experimental moisture content were compared layer by layer^{12,13}. The difference between the two is acceptable.

When the temperature rise by fan (1.2 – 1.5°C) is not included in the drying simulation, the drying rate is grossly underestimated when drying with near-ambient air (test runs nos. 5–9). This is due to the energy input at fan being the only source of energy input to the drying system. When drying air temperature increases (test runs nos. 10–11), the effect of temperature rise by fan is not significant. The simulated final moisture content is closer to the experimental one. This is due to the compensation between the underestimating drying rate by neglecting temperature rise by fan and the overestimating drying rate by the assumption of thermal equilibrium assumption.

Table 3 shows the comparison between the net specific final energy consumption for drying paddy obtained from the mathematical simulation and the experiment. The difference between the two is less than 20%, though the prediction is not very accurate. The mathematical model which was developed herein was then employed for further investigation of energy consumption patterns.

TABLE 2
COMPARISON BETWEEN EXPERIMENTAL AND SIMULATED MOISTURE
CONTENT OF PADDY DRIED BY VARIOUS DRYING STRATEGIES

Test no.	Air flow rate (m ³ /min-m ³ of paddy)	Total temperature rise (°C)	Initial moisture content (%wb)	Experimental final moisture content (%wb)	Simulated final moisture content (%wb)	Simulated final moisture content when temperature rise by fan is not accounted (%wb)	Calculated temperature rise by fan (°C)
5	2.27	1.5	18.3	14.0	15.2	16.9	1.5
6	2.27	1.2	15.2	14.2	14.1	14.6	1.5
7	2.17	0.9	18.7	14.2	14.0	15.3	1.4
8	2.21	2.5	20.6	14.2	15.2	16.9	1.5
9*	15.49	0.7	18.3	14.2	13.8	15.3	1.2
10	15.40	15.8	19.2	11.5	12.0	15.4	1.2
11	15.40	15.3	19.2	13.9	12.3	12.8	1.2

*Consider at the drying time of 42 hours instead of 60 hours as presented in Table 1

TABLE 3
COMPARISON BETWEEN EXPERIMENTAL AND SIMULATED NET
SPECIFIC ENERGY CONSUMPTION IN DRYING PADDY BY VARIOUS
DRYING STRATEGIES

Test no.	Experimental net specific energy consumption (MJ/kg water)			Simulated net specific energy consumption (MJ/kg water)		
	fan	heat	total	fan	heat	total
5	1.42	–	1.42	1.70	–	1.70
6	2.03	–	2.03	1.68	–	1.68
7	1.11	–	1.11	0.89	–	0.89
8	0.86	0.52	1.38	0.89	0.64	1.53
9*	2.34	–	2.34	1.88	–	1.88
10	0.32	2.36	2.68	0.23	2.84	3.07
11	0.36	2.53	2.89	0.26	3.04	3.30

*Consider at the drying time of 42 hours instead of 60 hours as presented in Table 1

2. Energy Analysis

Figure 1 shows the specific final energy consumption for various cases of drying conditions. The initial moisture content of paddy is 20% wet-basis. At the end of drying the average moisture content is 14% wet-basis. For each air flow rate, the thickness of grain bed is selected so that the pressure drop is not too high, i.e. less than about 3,000 Pa. The points to the left of each curve refer to the condition of drying without heater. For others, air is heated with the total temperature rise of 5, 10 and 15°C. It is limited at the temperature rise of 15°C because the head yield may be reduced significantly. Drying temperature should not be higher than about 45°C. To maintain the quality of paddy after drying, total dry matter loss is limited to not higher than 0.5%. Air condition of the month of September 1975, in Bangkok, which is the second worst during the period 1974–1983, was selected as the weather parameters for grain drying. It is a typical hot and humid weather condition. In order to get a reasonable comparison, the average value is used for the drying simulation. Simulated drying rate using the average weather parameters is nearly the same as the one using 3-hour interval weather parameters. The average ambient temperature and relative humidity are 27.6°C and 83%, respectively.

Fig. 1 Final specific energy consumption vs. temperature rise for different air flow rate

Fig. 2 Primary specific energy consumption vs. temperature rise for different air flow rate

At high air flow rate, $33 \text{ m}^3/\text{min-m}^3$ of grain utilization of energy is not efficient for drying with small temperature rise (Figure 1). This can be explained by Figure 3 which expresses the relationship between the moisture content at each layer and drying time. The drying rate of the top layer is nearly as fast as that at the bottom layer. The moisture content tends to approach the equilibrium moisture content. This means that the exhaust air is still dry and is capable of absorbing more moisture if the grain bed is deeper. However, the pressure drop will be too high if it is too much higher than grain bed depth of 0.58 m. As a result, it will not be easy to obtain the fan for this purpose or the fan may be too expensive. Three bed depths were simulated, i.e. 1 m, 0.58 m, and 0.5 m; the specific final energy consumption is nearly equal. At higher bed depth, it is slightly greater. This is because the efficiency of the electrical motor and heater are assumed to be 0.9 and 1, respectively. If they were the same, the energy consumption for each bed depth would be nearly equal. When the air is heated, the energy consumption is reduced and tends to be minimized when the temperature rise is about 15°C . This can be explained by Figure 4. It is obvious that the drying rate of the top layer is much slower than that at the bottom layer, meaning the moisture content of the top layer is nearly equal to the initial moisture content for most of the drying time. The exhaust air is much more humid compared to the previous case.

Energy consumption may be separated into two parts, i.e. electrical energy for driving fan and fuel for heating air. The latter, in general, is cheaper. Increasing the temperature rise does not only reduce the total energy consumption but also reduces the unit energy cost. The details of each part of energy consumption for various drying conditions are presented in Table 4.

The effect of initial moisture content on the energy consumption was also investigated (Table 4). The results are similar to those having the initial moisture content of 20% wet-basis.

When the air flow rate is reduced to about half, $16.5 \text{ m}^3/\text{min-m}^3$ of grain, the specific final energy consumption is reduced significantly (Table 4). The energy consumption patterns remain unchanged. There is no significant difference between the energy consumption for grain bed depths of 1 m and 0.84 m at the same temperature rise.

TABLE 4
SIMULATED RESULTS SHOWING ENERGY CONSUMPTION IN
DRYING PADDY FROM A GIVEN MOISTURE CONTENTS TO 14%
WET-BASIS. AVERAGE AMBIENT TEMPERATURE AND
RELATIVE HUMIDITY ARE 27.6°C AND 83%, RESPECTIVELY.

Air flow rate (m ³ /min-m ³)	Bed depth (m)	Temperature rise (°C)	Final energy consumption(MJ/kg)			Primary energy consumption(MJ/kg)			Dry matter loss (%)
			fan	heater	total	fan	heater	total	
a) Initial moisture content = 20% wet-basis									
3.3	2.00	1.5	2.28	-	2.28	7.28	-	7.28	0.50
		5.0	0.93	1.94	2.87	2.42	1.94	4.36	0.28
		10.0	0.49	2.51	2.99	1.27	2.51	3.78	0.20
		15.0	0.34	2.73	3.07	0.88	2.73	3.61	0.17
16.5	0.84	1.5	4.94	-	4.94	12.84	-	12.84	0.19
		5.0	1.16	2.43	3.59	3.02	2.43	5.45	0.09
		10.0	0.56	2.82	3.38	1.46	2.82	4.28	0.06
		15.0	0.36	2.93	3.29	0.94	2.93	3.87	0.05
33.0	0.58	1.5	7.85	-	7.85	19.71	-	19.71	0.15
		5.0	1.55	3.20	4.75	4.03	3.20	7.23	0.06
		10.0	0.68	3.41	4.09	1.77	3.41	5.10	0.04
		15.0	0.44	3.48	3.92	1.14	3.48	4.62	0.03
3.6*	2.00	1.5	1.50	-	1.50	3.90	-	3.90	0.50
b) Initial moisture content = 24% wet-basis									
33.0	0.58	1.5	6.22	-	6.22	16.17	-	16.17	0.44
		5.0	1.39	2.88	4.27	3.61	7.49	11.10	0.21
		10.0	0.61	3.05	3.61	1.59	7.93	9.39	0.14
		15.0	0.40	3.17	3.57	1.04	8.24	9.28	0.12

*Fan is operated with air relative humidity is less than 75%.

The efficiencies of electrical motor and heater are 90 and 100%, respectively.

Fig. 3 Moisture content vs. time

Fig. 4 Moisture content vs. time

Fig. 5 Moisture content vs. time

Fig. 6 Moisture content vs. time

Different results are obtained when the air flow rate is reduced ten times, $3.3 \text{ m}^3/\text{min}-\text{m}^3$ of grain. The specific final energy consumption is not significantly effected by temperature rise. This can be explained by Figures 5 and 6 which show that the moisture content of the top layer for both cases remains unchanged until very near to the end of drying. The energy consumption for the case of heated air (5, 10, 15°C) is slightly higher than the case of without heating. This may be due to the higher heat capacity of the grain bed and higher exhaust air temperature. Drying with high temperature rise may reduce energy cost due to lower cost of heat but it yields a greater moisture gradient between the bottom and the top layers. This is not suitable for in-store drying where the grain will not be transferred to other places after drying.

The specific final energy consumption can also be reduced by operating the fan only when the relative humidity of drying air is less than a set value, say at 75%. The results are shown in Table 4. The energy consumption is reduced significantly when compared to that of continuous run (1.50 MJ/kg vs. 2.28 MJ/kg). In both cases, the heater is not used and the total dry matter loss at the end of drying is 0.5%. However, the moisture gradient for the case of on-off fan is slightly greater than the case of continuous run. It is because air flow rate is higher (3.6 vs. $3.3 \text{ m}^3/\text{min}-\text{m}^3$ of grain). This results in higher temperature rise by shaft work.

Energy consumption in terms of primary energy can be obtained by multiplying the electrical energy with a conversion factor. In this study, it is 2.6. The effect of temperature rise and air flow rate on the specific primary energy consumption is presented in Figure 2 and in Table 4 as well. The results show that the energy consumption decreases when the temperature rise increases and tends to be at a minimum for temperature rise of 15°C. At the same level of temperature rise, drying with low air flow rate consumes less energy compared to drying with high air flow rate. When the temperature rise is higher than 5°C, drying with low air flow rate consumes less energy than drying with high air flow rate at any drying temperature.

The effect of ambient air condition on the energy consumption patterns was investigated by employing the mathematical model. Air relative humidity was reduced from 83% to 73% while temperature was kept constant at 27.6°C. The new drying air condition has higher potential of drying. The simulated results are presented in Figures 7-10 and Table 5.

TABLE 5
SIMULATED RESULTS SHOWING ENERGY CONSUMPTION IN
DRYING PADDY FROM THE MOISTURE CONTENT OF 20% TO 14%
WET-BASIS. AVERAGE AMBIENT TEMPERATURE AND
RELATIVE HUMIDITY ARE 27.6°C AND 73%, RESPECTIVELY.

Air flow rate (m ³ /min-m ³)	Bed depth (m)	Temperature rise (°C)	Final energy consumption(MJ/kg)			Primary energy consumption(MJ/kg)			Dry matter loss (%)
			fan	heater	total	fan	heater	total	
3.3	2.00	1.5	1.59	-	1.59	4.13	-	4.13	0.35
		5.0	0.76	1.60	2.36	1.98	1.60	3.58	0.24
		10.0	0.44	2.25	2.69	1.14	2.25	3.39	0.18
		15.0	0.31	2.52	2.83	0.81	2.52	3.33	0.15
33.0	0.58	1.5	3.24	-	3.24	8.42	-	8.42	0.09
		5.0	1.27	2.63	3.90	3.30	2.63	5.93	0.05
		10.0	0.63	3.19	3.82	1.64	3.19	4.83	0.04
		15.0	0.42	3.33	3.75	1.09	3.33	4.42	0.03

The efficiencies of electrical motor and heater are 90% and 100%, respectively.

TABLE 6
QUALITY OF PADDY AFTER DRYING BY VARIOUS STRATEGIES *

Test no.	Air flow rate (m ³ /min-m ³)	Air temperature (°C)	Head yield (%)
1	4.11	36.0	59.1
2	1.32	42.1	58.0
3	2.98	33.8	56.0
4	2.62	33.3	61.3
5	1.39	33.5	64.1
6	1.80	35.2	45.5
7	1.84	35.1	60.4
8	1.49	32.7	52.8
9	16.46	42.7	59.4
10	10.09	44.8	57.5
11	9.81	43.9	59.0

*Modified from Soponronnarit (1987)

From Figure 7, drying with near-ambient air consumes lower specific final energy for both low and high air flow rates when compared to drying with higher air temperature. The result, particularly for high air flow rate, is different from the case of higher value of ambient relative humidity where final energy consumption at near-ambient air is higher than that at higher temperature. This can be explained by Figure 9 which shows that the moisture content of the bottom, middle, and particularly the top layer is still far from the equilibrium moisture content. As a result, there is no loss of drying efficiency. At higher air temperature, the moisture content of the three layers is also far from the equilibrium one (Figure 10). However, the specific final energy consumption is higher. This may be due to higher heat capacity of the grain bed and higher exhaust air temperature. Drying with low air flow rate consumes lower specific final energy when compared to higher air flow rate (Figure 7) and this is also true for the specific primary energy consumption as presented in Figure 8.

3. Quality of Paddy

According to the result of energy consumption, drying paddy with low air flow rate and near-ambient air seems to be of the most interest strategy. However, quality of paddy after drying should also be considered. Soponronnarit (1987) investigated the effect of air flow rate and temperature on the head yield of paddy after milling. The details are presented in Table 6. It was found that the head yield varied from 53–64% (except test no. 6) for the ranges of air flow rate from 1.32 to 16.46 m³/min per m³ of grain and of temperature from 32.7 to 44.8°C. Due to the effect of the history of paddy before drying which is different among each test, it is unable to indicate that which drying strategy is the best in terms of head yield. However, these figures are very high when compared to the case of direct sun drying.

4. Capacity of Dryer

When energy consumption and paddy quality are considered together, drying with low air flow rate and near-ambient air seems also to be the most of interest. However, drying process takes place so slow and thus reduces the drying capacity of dryers. This problem can be avoided if paddy is dried in storage bins. This means that the grain will be dried in the storage bin and then stored in the same storage bin after drying completed.

Fig. 7 Final specific energy consumption vs. temperature rise for different air flow rate

Fig. 8 Primary specific energy consumption vs. temperature rise for different air flow rate

Fig. 9 Moisture content vs. time

Fig. 10 Moisture content vs. time

CONCLUSION

1. The mathematical model developed herein predicts the drying rate with acceptable accuracy when air flow rate and temperature are low. The drying rate is overestimated when air flow rate is high and significant if air temperature is also high.

2. The mathematical model developed herein predicts the specific energy consumption with an error less than 20%.

3. For a typical study on paddy drying, low air flow rate is preferred. The air should be heated with a temperature rise of 5°C only when the ambient air is humid. This recommended drying strategy will result in low final and primary energy consumption and low moisture gradient in the grain bed as well. Also head yield is expected to be high. The grain should be dried in storage bins where it will be stored after drying completed.

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ANNEX A

SIMULATION FLOW CHART

ANNEX B

NOMENCLATURE

Symbol

c	- specific heat, kJ/kg°C or J/kg°C
D	- density, kg/m ³
Dh	- rate of enthalpy change, kW
DML	- dry matter loss, decimal
Dt	- time interval, h
DT	- temperature rise, °C
E	- efficiency, decimal
h	- enthalpy, kJ
m	- mass flow rate, kg/s
M	- moisture content, decimal dry basis
M_w	- moisture content, decimal wet basis
P	- pressure, Pa
Q	- heat flow rate, kW
R	- mass ratio of grain to air, kg dry matter/kg dry air
RH	- air relative humidity, decimal
t	- time, h
T	- temperature, °C
TP	- grain temperature, °C
v	- specific volume, m ³ /kg of dry matter
V	- velocity, m/min
W	- humidity ratio, kg H ₂ O/kg dry air
W_s	- shaft power, kW

Subscript

a	- air, ambient
bd	- after thermal equilibrium
eq	- equilibrium
f	- final, fan
in	- initial
pw	- wet grain
t	- total
v	- vapor