시뮬레이숀에 의한 벼의 常温通風層乾燥方法에 關한 硏究

Simulation of Natural Air Layer Drying of Rough Rice

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摘要

常溫通風을 利用한 In-bin drying에 對한 많은 實驗結果에 依하면 우리나라 10月의 氣象條件은 低溫乾燥 system에 適合한 乾燥能力을 가지고 있는 것으로 나타났다. 最近 Computer를 利用한 Simulation model이 開發되어 乾燥現象에 關한 經濟的이고 效率的인 分析이 可能하게 되었다. 이러한 分析結果에 依하면 初期含水率이 높은 벼를 Full-bin을 利用한 常溫通風乾燥를 할 境遇 乾燥期間이 길어지며 bin內의 上層部 穀物이 變質되는 問題點이 發生하였다. 또한 벼의 收穫作業體系가 慣行 및 Binder作業體系에서 漸次 Combine作業體系로 轉換되어감에 따라 圃場에서의 乾燥가 어려우며 刈取, 脫穀作業過程에서의 機械的인 穀物 損失을 줄이기 爲하여 含水率이 比較的 높은 벼를 收穫하여야 한다.

本 硏究의 目的은 常溫通風乾燥에 있어서 乾燥能力을 增加시키기 爲하여 穀物을 一定期間 나누어서 bin에 넣고 乾燥를 하는 Layer drying의 Simulation model을 開發하고 이 Model에 水原地方의 7年間 平均 氣象資料를 入力시켜 穀物의 初期含水率, 投入量, 投入期間의 變化에 따른 Layer drying現象을 糾明하는데 있다.

Simulation에 使用된 bin의 크기는 直徑 2m, 길이 1.5m이며 送風팬의 容量은 0.5HP이었다.

Simulation分析 結果를 要約하면 다음과 같다.

(1) Layer drying의 Simulation model을 開發하였으며 이 Model은 벼의 常溫通風乾燥 實驗에서 含水量 變化의 理論値와 實際實驗値가 잘 一致하였다.
(2) 穀物投入期間 1日을 Full-bin drying으로 看做할 때 Layer drying의 乾燥性能은 Full-bin보다 높은 것으로 나타났다.
(3) 連續送風(24時間)을 할 境遇 穀物投入期間이 增加함에 따라 乾燥期間의 減小傾向은 斷續送風인 境遇보다 적었지만 乾燥期間은 短縮되었다. 그러나 乾燥에너지의 消耗는 斷續送風일 때보다 크게 나타났다.
(4) 斷續送風(9：00AM～6：00PM)일 境遇 穀物投入期間을 增加시키면 乾燥期間이 크게 줄어 들었다.
(5) 穀物의 初期含水率이 21% 以下일 境遇 連續 및 斷續送風에서 乾燥期間의 差異가 별로 없었다.
(6) 穀物의 初期含水率이 높으면 Full-bin drying에서는 上部層에 穀物이 變質될 憂慮가 있으나 Layer drying에서는 穀物投入量을 調節하면 이것을 防止할 수 있었다.
(7) 乾燥가 完了된 後 層別 最終穀物 含水率은 모든 乾燥條件에서 同一하였으나 bin의 下部層은 過乾燥 物象을 일으켰다.

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Ⅰ. Introduction

The conventional method of drying of rough rice in Korea has been sun drying in the field before threshing and on mats after threshing. However, the sun drying has problems of quality and quantity losses during drying, and high labour requirements. Chung(1980) reported in his study on the rice post-production system in Korea that rice post-production grain losses to the total yield were an average of 3-5% for the harvest losses, 2-3% for the storage losses and 4-6% for the milling losses, totaling a little over 11%. Such amount of grain losses is of considerable economic importance to the Korean farmers.

Particularly, since new rice varieties having high yield potential and easily shattering characteristics were introduced into Korea in 1969, it has been continuously pointed out that the traditional sun during practice should be improved.

Early cutting and wet threshing in the field with binder or combine harvesters as being practiced in the developed countries have been tried as a new harvesting system to reduce the field loss. For this new harvesting system, the in-bin grain drying and storage system which is capable of drying grains of high moisture content and preventing them from the damage by rodents and insects has been recommended.

Either a heated-air or an ambient air temperatures can be used for the in-bin grain drying and storage systems. However, low temperature drying systems have been extensively used for drying cereal grain after the energy crisis in 1973.

Recently, in Korea, the improvement of paddy drying system is needed in accordance with the mechanization of rice harvesting system. A limited number of grain dryers are being used by the farmers, but they are not popular to the farmers, mainly because of high purchase and operating costs.

Natural air condition in Korea was found to have good moisture holding capacity enough to make an in-bin drying with ambient air feasible, but few attempts have been made for the natural air drying. Some theoretical studies with simulation models were conducted for the analysis of the natural air drying. Keum(1979) and Han(1980) developed computer simulation models to determine the technical feasibility of the natural air drying, and proved that natural air could be used with the full-bin system in which the fan was operating continously until the moisture content of the grain at the top layer of the bin reaches a safe moisture level for storage. Two problems to be solved in their experiments were how to extend the drying time when the initial moisture content of the grain was high and how to reduce deterioration that may occur before all the grains in the bin could be dried up to a safe storage moisture content.

Layer drying has long been recongnized as a means of increasing the drying potential of low temperature drying systems. Harvesting schedule with a combine can also be controlled if the layer drying is adapted.

The purpose of this study was:

(1) to develop a simulation model for the natural air layer drying of rough rice,

(2) to conduct experiments for the validation of the simulation model,

(3) to analyze the effects of the initial moisture contents and grain loading intervals on the drying performance,

(4) to compare the layer drying with the full-bin drying of rough rice.

Ⅱ. Review of Literature

A. Layer Drying of Grain

In the layer drying process, an initial grain load is placed in the bin and drying is begun. Other grain loads are added periodically above first load. The bin is eventually filled and drying is continued until the drying zone has passed through the grain mass.

The first load placed in the bin usually has the highest initial moisture content and they receive highest airflow rate because grain depth is shallow. The last grain added usually has the lowest moisture content of the grain placed in the bin, and the airflow rate is lowest during this stage of the process because depth is greatest.

In the low temperature system with natural air, especially, layer drying has been used to increase the drying potential. The advatages of the layer drying are as follows.

(1) Grain with a higher initial moisture content can be harvested, as compared to the maximum initial moisture content used in full bin drying.

(2) The drying period is shorter than with full bin drying if grain with the same initial moisture content is harvested. But layer drying needs a careful management and may restrict the harvesting schedule.

Pierce and Thompson (1980) conducted the simulation to investigate the layer drying of corn as a method of increasing drying potential and reversing airflow direction. They found there was a greater advantage to using layer drying, with regard to the ability to handle wetter grain, for the earlier harvesting dates.

B. Simulation Models on Natural Air Drying System

Grain drying is especially affected by drying conditions such as initial moisture content, weather data, air flow rate, and bin depth. It is difficult to calculate the exact drying time for a particular drying season. As a result, a number of computational models for heat and mass transfer in deep beds of biological material have recently been developed.

Thompson and Peart (1968) presented the mathmatical drying model to predict the performance of three type grain dryers. This study was followed by many papers on the drying simulation, storage models, and temperature control system.

Morey and Peart (1971) used the Thompson in-bin simulation model to determine the least cost systems for drying corn with natural air. Bloome (1970, 1971) developed a model for simulation of heat and mass transfer in deep beds of shelled corn under near equilibrum conditions.

Alam (1971) used Bloome model to soybean drying. Experimental model validation was performed and its result was not accurate. He concluded that complete equilibrium had not reached in the first layers but might be reached in the final layers. He modified Bloome model by adjusting the absolute humidity of air going into each layers.

Maurer (1977) suggested the mass diffusion drying model based on the Newton's law of cooling, and validated three basic drying models (equilibrium, moisture ratio, mass diffusion models).

Chang (1978) made several modifications to the Mourer's simulation model to simulate rough rice drying with natural air.

Keum (1979) developed rough rice drying model based on the mass diffusion theory with natural and solar-heated air.

Han (1980) developed the rough rice drying model by the application of mass diffusion theory and determined the minimum air flow rate for a fixed bin diameter. In this study, his model was modified to develop the simulation model of the rough rice layer drying.

Ⅲ. Modeling of Rough Rice Layer Drying System

A. Introductory Remark

Grain drying is a continuous process where moisture content, air and grain temperature and the humidity of the air change simultaneously.

Equations describing the exchange of heat and mass between grain and drying air was solved numerically based on the assumption that each of the thin layers is combined to form the deep bed of the grain mass. If the air conditions flowing into the layer are known and conditions of the entering air do not change for a finite time interval, a thin layer drying model can be used to determine the change in the grain moisture, layer by layer, in a deep bed drying system.

A schematic diagram of the simulation approach employed in this study is shown in Figure 1. In this system, the following five initial values are known:

(1) TI = initial air temperature (°C)

(2) AHI = initial absolute humidity of air(kg, H_2O/kg, dry air)

(3) RHI = initial relative humidity of air (decimal)

(4) GT = initial grain temperature (°C)

(5) MC = initial grain moisture content (decimal, d.b.)

and the four final values are unknown;

(1) GTF = final air and grain temperature(°C)

(2) MCF = final grain moisture content (decimal, d.b.)

(3) AHF = final absolute humidity of air (kg,H_2O/kg, dry air)

(4) RHF = final relative humidity of air (decimal)

Thus, four equations were used to determine the four unknown values.

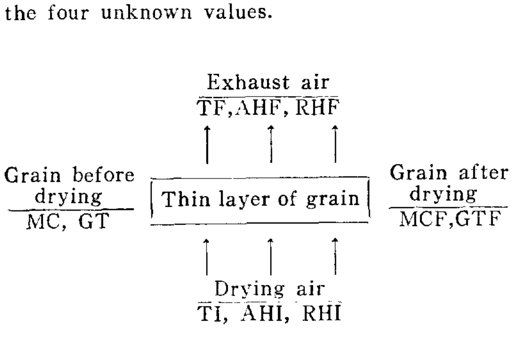


Fig. 1. Schematic diagram of simulation approach.

B. Assumptions

Flolowing assumptions were made for the simplification of the simulation;

(1) Mass diffusion is the governing process for the natural air drying.

(2) Temperature and moisture gradients within the bed particles are negligible.

(3) The bin is assumed to be air-tight and the exhaust air from one layer is an input to the next layer.

(4) Final air temperature is equal to final grain temperature.

(5) No temperature and moisture gradients exist in the radial direction of the grain bed.

(6) Heat transfer is adiabatic with no conduction losses laterally from the layer.

(7) The total mass of the system remains constant and mixing does not occur between layers.

(8) A three-hour time interval will insure that equilibrium is achieved.

C. Equations Involved in Simulation Model

1) Mass diffusion equation

In grain drying, the rate of drying is assumed to be proportional to the drying potential of the grain. It is similar to Newton's law of cooling. The drying potential may be considered as the pressure difference in vapor between grain and air. Thus the equation for the drying rate may be written as follows;

$$\frac{dM}{dt} = -DC*(VPG-VPA)$$

or,

$$MCF = MC - DC*t*(ERH*SVP(GT) - RHI*SVP(TI))$$

where MC, MCF = initial and final grain moisture contents (decimal, d.b.)

DC = mass diffusion coefficient (decimal, d.b./hr.KPa)

t = time increment (3hr)

VPG = vapor pressure of the grain (KPa)

VPA = vapor pressure of the air (KPa)

ERH = equilibrium relative humidity (decimal)

RHI = relative humidity of the air (decimal)

SVP(GT) = saturated vapor pressure at grain temperature, GT (KPa)

SVP(TI) = saturated vapor pressure at initial air temperature, TI (KPa)

With a number of grain drying tests, the diffusion coefficient was not consistent.

Maurer (1977) found that the diffusion coefficent of $2.9*10^{-8}$ was fit very well for describing the drying phenomena when the moisture content of the grain is above 15.5% (w.b.).

2) Equilibrium relative humidity

The equilibrium relative humidity for the grain was calculated from either the Chung-Pfost or Henderson-Thompson ERH equations.

Chung-Pfost equation:

$ERH=EXP(-A*EXP(-B*MC)/R/(GT+C))$

Henderson-Thompson equation:

$ERH=1-EXP(-K*(GT+CT)*(MC*100)^{n})$

where REH = equilibrium relative humidity of the grain at GT, MC(decimal)

R = universal gas constant (1.987Kcal/kg-mole. K)

MC = moisture content of the grain (decimal, d.b.)

A = 1181.57

B = 21.733

C = 35.703

K = 1.918E-05

n = 2.4451

CT = 51.161

3) Heat balance equation

The final temperature was computed from the heat balance equation, which simply states that the initial heat content of the system is equal to the final heat content(Thompson,1972):

$$CA*AIR*TI+WAIR*AHI*(2501.0+1.775*TI)+CO*WG*(1+MC)*GT=CA*WAIR*GTF+WAIR*AHF*(2501.0+1.775*GTF)+CF*WG*(1+MCF)*GTF$$

or,

$$GTF=(CA*WAIR*TI+WAIR*AHI*(2501.0+1.775*TI)+CO*WG*(L+MC)*GT-2501.0*WAIR*AHF)/CA*WAIR+1.775*WAIR*AHF+CF*WG(1+MCF))$$

where TI = initial air temperature(°C)

GT = initial grain temperature(°C)

GTF = final air and grain temperatures (°C)

CA = specific heat of air(1.006KJ/kg.°K)

CO,CF = initial and final specific heat of the grain(KJ/kg.°K)

4) Specific heat of rough rice

Specific heat of rough rice was calculated by Morita's equation(1979):

$CO=4.1855*(0.3032+0.833*M)$

where M = moisture content of rough rice (decimal, w.b.)

5) Other equations

In addition to the equations mentioned above, other equations were used in simulating grain drying. These include the equations of the psychrometric properties of the air and bulk density of the rough rice.

To determine the psychrometric properties of air the following equations reported by Brooker (1974) were used:

$VP=RH*SVP$

$AH=0.6219*VP/(ATM-VP)$

$VAIR=2.833E-3*TK*(1+1.6078*AH)$

where VP = vapor pressure of the air (KPa)

RH = relative humidity of the air(decimal)

SVP = saturated vapor pressure of the air (KPa)

AH = absolute humidity of the air(kg, H_2O/kg, dry air)

ATM = atmospheric pressure (101.325KPa)

VAIR = specific volume of the air(m^3/kg, dry air)

TK = absolute temperature of the air(°K)

Bulk density of the rough rice was calculated by the following equations developed by Wratten et al. (1969):

For long grain:

$$DENSY=519.446+5.29*M$$

For medium grain:

$$DENSY=499.696+8.33*M$$

where DENSY = bulk density of the rough rice (kg/m^3)

M = moisture content(percent, w.b.)

These equations can be chosen by the input parameter.

D. Dry Matter Loss

Grain deterioration is caused by the respiration of the grain itself and other microorganisms. Respiration is a process that produces heat, water and carbon dioxide. Dry matter of grain is lost by the formation of carbon dioxide which is resulted from the combustion of carbohydrate.

The combustion of a typical carbohydrate is as follows:

$$C_6H_{12}O_6+6O_2=6CO_2+6H_2+677.2Kcal$$

Murata (1976) measured the heat produced by the respiration of rough rice. The respiration heat was depending on the grain moisture and temperature, and was expressed as the following equaion:

$$HEAT=EXP(A*T^2+B*T*M+C*M^2+D*T+E*M+F)$$

where HEAT = respiration heat (Kcal/kg, dry matter. hr)

T = temperature of the grain (°C)

M = moisture content of the grain (percent, w.b.)

$A=-1.11339E\text{-}03$

$B=1.11532E\text{-}03$

$C=-0.5820E\text{-}02$

$D=0.08708$

$E=0.41470$

$F=010.85623$

Since 677.2 Kcal/kg of respiration heat is produced from complete oxidation of 180g/kg of dry matter, one Kcal/kg of respiration heat from 26.58g/kg or 0.02658 percent of dry matter decomposition. Therefore, the dry matter loss can be calculated by the following equation:

$$DML=0.02658*HEAT*t$$

where DML = dry matter loss (percent)

t = time increment (3hr)

Total dry matter loss (TDML) is the sum of DML during the total drying period.

The temperature and moisture content of the grain increase due to the heat and water produced by the combustion of carbohydrate. Since 15.74 KJ of heat results from one kg of dry matter loss, and 0.6 percent moisture content increase results from one percent of dry matter loss, increases in temperature and moisture of the grain due to dry matter loss can be obtained as follows:

$$DTDML=DML*0.01*15.74*WGD/WG/CO$$

or,

$$DTDML=DML*0.01*15.74*(1-M)/CO$$

$$MCF=(MCF+0.006*DML)/(1-0.01*DML)$$

where DTDML = temperture increase of the grain due to dry matter loss (°C)

WGD = dry matter of the grain (kg)

WG = total weight of the grain (kg)

CO = specific heat of the grain(KJ/kg.°C)

M = moisture content of the grain(percent, w.b.)

MCF = final moisture content of the grain (percent, d.b.)

E. Success Criterion for Layer Drying Simulation

According to Saul's study (USDA, 1968), 0.5 percent dry matter loss makes the corn lose some quality but keep its market grade. Thus, 0.5 percent dry matter decomposition is about the limit without any reduction in grade.

It was considered that drying was successfully completed when the top layer of the final grain load was dried to 15 percent of moisture content, (w.b.), and the total dry matter loss did not exceed 0.5 percent at that time.

F. Computer Simulation Program

A layer drying simulation program was developed with FORTRAN languages using all the

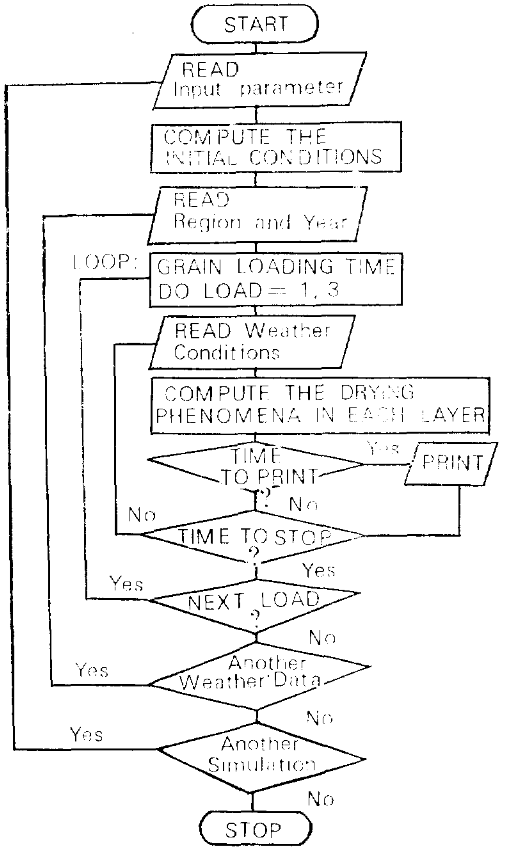


Fig. 2. Schematic flow chart of the simulation program

equations previously described. Fig.2 shows the simplified flow chart of the program.

The simulation program consists of;

1) Main Program
2) OUTPUT Subroutine: control of output options
3) PSYCHR Subroutine: calculation of psychrometric properties of inlet air
4) DIFFUSE Subroutine: solution of the mass diffusion phenomena
5) DMLOSS Subroutine: computation of dry matter loss
6) ADJUST Subroutine: correction of the final relative humidity
7) GRAPH 1
   GRAPH 2
   GRAPH 3 Subroutine: making and writing
   ARRANGE the graphic array
   ARRANGE 1
   ARRANGE 2
8) ERHQ Function: calculation of the equilibrium relative humidity
9) SHEAT Function: calculation of specific heat of rough rice
10) SVP Function: calculation of saturated vapor pressure

Input data to the simulation program consists of:

1) Initial grain temperature (°C)
2) Initial grain moisture content (%,w.b.)
3) Airflow rate of each loading (cmm/cu.m)
4) Grain depth of each loading (m)
5) Grain loading interval (days)
6) Bin diameter (m)
7) Temperature increment (°C)
8) Fan operation method;
   1=continuous fan operation
   2=continuous fan operation until top layer was dried to 16% (w.b.) of moisture content, and then intermittent.
9) Designation number of ERH equation
   1=Chung-Pfost equation
   2=Henderson-Thompson equation
10) Designation number of density equation
   1=equation for long grain of rough rice.
   2=equation for medium grain of rough rice.
11) Type of output form;
   1=detailed three-hour basis output (w.b.)
   2=daily output (w.b. at 9 : 00 AM)
   3=daily graphic output of moisture content of each layer
   4=daily graphic output of average moisture content and dry matter loss of each grain loading
12) Weather condition (three-hour basis dry bulb temperature and relative humidity)

Ⅳ. Simulation Model ModiFication and Validation

In order to apply the simulation model to rough rice layer drying system, the model validation must be necessary. Verifying the validity of the simulation model involved that the data collected from actual drying test were compared with those calculated from the simulation model developed in this study.

The actual drying test was conducted from Sept. 28 to Oct. 17, 1982. The drying bin was placed in the laboratory and the air was supplied from outside. The drying conditions are given in Table 1 and the experimental apparatus is shown in Fig. 3. The round steel drying bin equipped with steel perforated floor was used for the test. The bin was 0.57m in diameter and 1.5m in height, and 0.5hp vane axial fan was used to supply air through the grain mass. The air chamber was installed near the grain bin for adjusting the flow rate.

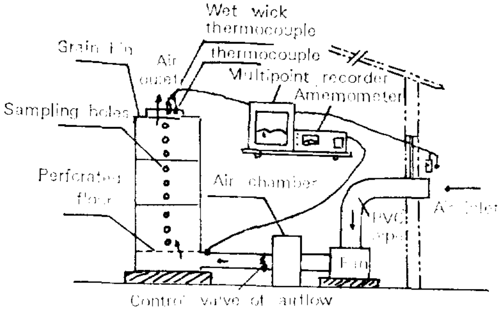


Fig. 3. Schematic diagram of grain bin for the rough rice of layer drying in the laboratory

Table 1. Drying conditions used for the validation test of layer drying model (Oct. 1982)

Item	Grain loading		
	1st	2nd	3rd
Initial moisture content (%, w.b.)	22.0	22.5	22.0
Initial grain temperature (°C)	22.0	22.0	22.0
Unit airflow rate (cmm/cu.m)	11.0	4.2	3.0
Grain loading weight(kg)	76.9	80.8	74.5
Grain depth(m)	0.50	0.55	0.45
Grain loading interval(day)	0	3	3
Bin diameter (m)	0.57	0.57	0.57
Bin height (m)	1.5	1.5	1.5

Table 2. The agronomic data of the rough rice used for layer drying(Oct. 1982)

Variety	Akibare
Sowing date	April 16, 1982
Transplanting date	May 24, 1982
Harvesting date	September 28, 1982

The rough rice sample used in this experiment was harvested with a self-feeding type combine. The specifications of the sample are shown in Table 2.

The bin was filled with three load levels of 76.9, 80.8, and 74.5kg, at 3 day interval. Initial moisture content of the grain of each load was 22.0, 22.5, and 22.0% (w.b.) respectively. Airflow rates with lst, 2nd, and 3rd, load in the bin were 11.0, 4.2, and 3.0cmm/m^3. Two thermocouples, one with a wet wick, were mounted at the outlet and inlet of the bin to check the air conditions. Airflow were measured with a hot-wire anemometer.

Samples of rough rice were taken when loading the bin and moisture content was determined at nine different locations in the bin at 9 o'clock every morning. Moisture was determined using oven drying method for 48 hr at 103°C.

The fan was operated continuously from 9 : 00 AM to 6 : 00 PM every day whenever the relative humidity was below 75 percent. Weather data, recorded on 3-hr basis in Suweon area, were used for the experimental analysis.

Unfortunately, the predicted values from the simulation model were not well agreed with the experimental results. In the bottom layers of the bin, moisture gradients estimated by simulation model were quite similar to those experimentally observed. However, the deviations between the actual and predicted values increased in the middle and top layers. The moisture content of the grain in the middle and top layers in the actual test was 2 or 3% (w.b.) higher than that predicted. Consequently, the drying rate of the simulation model was faster than that observed in the experiment.

Therefore, in order to modify the simulation model, the coefficient of the mass dffusion was varied from 2.9×10^{-3} to 2.1×10^{-3} (decimal d.b./KPa) with an interval of 0.1×10^{-3} until good simulation result was obtained. When the coefficient was $2.2. \times 10^{-3}$, the simulation model was verified to be the most accurate. So the coefficient of the mass diffusion was modified to 2.2×10^{-3} for the analysis. The result obtained by this modified simulation model was very well agreed with the actual data.

The comparison of the results obtained from

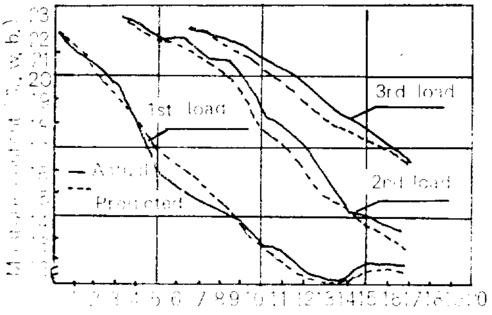


Fig. 4. Comparision of the actual and predicted average moisture content of rough rice in each load (Oct. 1982).

Table 3. Comparison between the actual and predicted average moisture content of rough rice in each load (Oct. 1982)

drying time (days)	1st load			2nd load			3rd load		
	A	P	D	A	P	D	A	P	D
1	21.2	21.2	−0.1						
2	20.3	20.0	0.3						
3	19.6	19.0	0.6						
4	17.7	17.8	0.1	22.1	22.0	0.1			
5	15.5	16.8	−1.3	21.6	21.6	0.0			
6	15.0	16.4	−1.4	21.8	21.4	0.4			
7	14.5	15.6	1.1	20.8	20.8	0.0	22.0	21.9	0.1
8	14.3	14.5	−0.2	20.9	20.0	0.9	21.8	21.0	0.8
9	13.8	13.6	0.2	19.7	19.2	0.5	21.4	20.8	0.6
10	12.5	12.5	0.0	18.4	18.0	0.4	20.9	20.5	0.4
11	12.4	12.0	0.4	17.9	17.2	0.7	20.6	19.9	0.7
12	11.7	11.5	0.2	17.0	16.0	0.1	19.8	19.0	0.8
13	11.0	11.2	−0.2	15.7	15.0	0.7	19.1	18.5	0.6
14	11.2	11.0	0.2	14.1	14.2	−0.1	18.4	18.0	0.4
15	12.1	11.7	0.4	14.0	13.8	0.2	18.2	17.5	0.7
16	12.1	11.9	0.2	13.8	13.4	0.4	17.2	17.0	0.2
17	12.1	11.7	0.3	13.5	12.8	0.7	16.2	16.0	0.2
$S\bar{D}$			0.605			0.316			0.253
t			−0.014			1.132			1.976

Note; A : Actual moisture content (percent, w.b.)
P : Predicted moisture content (percent, w.b.)
D : Difference (Actual value-predicted value)
$S\bar{D}$: Standard deviation
t : Computed t-value

the actual drying test and simulation results were shown in Table 3. Statistical analysis indicated that there was no significant difference between the actual and predicted moisture content. Fig. 4 was the graphical presentation of Table 3.

From the result compared with actual and estimated test, this modified simulation model may considered to be valid for the simulation of the layer drying of the rough rice by natural air.

V. Simulation Application

In the natural air drying system, the main factors affecting the layer drying performance are considered as follows;

(1) Initial moisture content of the grain

(2) Grain loading rate

(3) Airflow rate

(4) Harvesting date

(5) Ambient weather condition

Layer drying performance is specfic situation because it is dependent upon the airflow rates delivered at various depths of fill.

The following assumptions were made for the convenience of analysis of the drying results.

(1) The suitable bin size for Korean farmers was assumed to be 2.0m in diameter and 1.5m in depth.

(2) It was assumed that the bin was filled three times with equal eize of loads which are equivalent to 0.5m in bin depth at a given loading interval.

(3) The reduction of grain moisture in the field was assumed to be 0.5% (w.b.) per day.

(4) The fan was 0.5 hp, centrifugal type and the variation of the airflow rate for a given grain load is shown in Fig.5.

(5) The harvesting date of the grain was Oct. 1.

(6) Average weather conditions in October over 7 years in Suweon were used for the simulation results. The weather data are shown in Table 4.

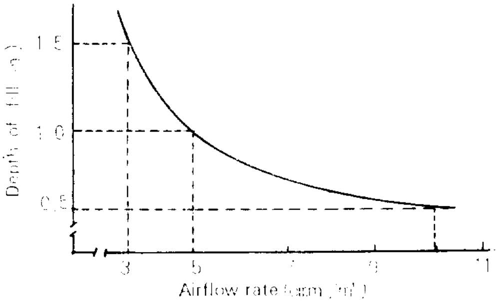


Fig. 5. Relationships between grain depth and airflow rate.

Two methods of fan operation were used. Firstly, the fan was operated continuously until the moisture content of the grain at the top layer was below 15% (w.b.). Secondly, the intermittent fan operation was empolyed, in which the fan was operated from 9 : 00 AM to 6 : 00 PM during drying period.

About 1.1°C of the temperature rise was obtained during the drying operation which was resulted from the heating effect by the electric motor. The criteria to determine whether drying was successfully completed or not, were that the grain moisture content at the top layer of the bin reached below 15% (w.b.) and the dry matter loss was below 0.5%.

Table 4. Average weather data in October over 7 years (Seweon area)

Year	1973	1974	1975	1976	1977	1978	1979	Ave.	SD*
Temperature(°C)	12.0	11.3	14.3	12.6	14.9	13.3	14.2	13.2	4.32
Relative humidity(%)	75.8	78.4	76.0	74.5	76.2	76.9	73.6	75.9	15.03

*SD=standard deviation

Table 5. Simulation results

Grain loading Interval (days)	Initial moisture content (%, w.b.)	Continuous fan operation					Intermittent fan operation				
		Drying time (days)	Final average moisture content (%, w.b)			DML	Drying time (days)	Final average moisture content (%, w.b.)			DML
			1st load	2nd load	3rd load	%		1st load	2nd load	3rd load	%
1	24	22	12.2	12.8	14.0	0.37	30	11.9	12.2	13.9	0.62*
	23	20	12.2	13.0	14.2	0.29	27	11.8	12.3	13.7	0.50
	22	19	12.0	12.8	14.0	0.24	24	11.7	12.0	13.9	0.39
	21	17	12.4	13.2	14.4	0.19	21	11.9	12.4	14.1	0.30
	20	16	12.2	13.2	14.4	0.15	19	11.8	12.5	14.0	0.23
2	24	21	12.0	12.8	14.0	0.25	26	11.9	12.2	14.0	0.40
	23	19	11.9	12.8	14.2	0.21	23	11.8	12.4	14.3	0.32
	22	18	11.8	13.0	14.2	0.18	21	11.7	12.4	14.0	0.26
	21	16	12.2	13.2	14.4	0.12	19	11.8	12.4	14.1	0.21
	20	14	12.6	13.6	14.6	0.12	16	11.9	12.8	14.2	0.16
3	24	20	11.9	13.0	14.4	0.25	25	11.8	12.4	14.0	0.38
	23	19	12.0	12.8	14.2	0.21	22	11.6	12.5	14.2	0.31
	22	17	12.4	13.4	14.2	0.18	20	11.9	12.6	14.2	0.25
	21	16	12.2	13.2	14.4	0.15	18	11.7	12.7	14.2	0.20
	20	14	12.4	13.6	14.6	0.12	15	11.9	13.4	14.6	0.16
4	24	20	12.0	13.0	14.4	0.25	24	11.8	12.6	14.2	0.38
	23	19	11.9	12.9	14.2	0.21	21	11.7	12.7	14.4	0.31
	22	17	12.2	13.4	14.6	0.18	19	11.9	12.8	14.5	0.25
	21	15	12.4	13.6	14.8	0.15	16	12.0	13.6	14.6	0.20
	20	14	12.4	13.6	14.6	0.12	13	12.6	14.2	14.8	0.12

***Note** ; only case when failure occurred.

Ⅵ. Results and Discussions

A. Effect of Initial Moisture Contents

In the low temperature drying system the initial moisture content of the grain and the airflow rate greatly affects the drying performance. Generally, an increase in the initial moisture content of the grain with a given minimum airflow increased the drying time.

Table 5 presents the simulation results for various drying conditions. As shown in Table 5, the drying time was 22 days for continuous fan operation method while it was 30 days for intermittent fan operation method at the same initial moisture content of 24% (w.b.) and for the same grain loading interval of one day. Furthermore, 0.62% of dry matter loss was occured in the intermittent fan operation. If the grain loading interval increased, however, the drying could be completed successfully even though longer drying time required. This would indicate that higher moisture content of the grain could be dried successfully by increasing the grain loading interval.

The final moisture content of the grain at each load was almost the same in all cases and was not affected by the initial moisture content of the grain. However, overdrying occurred at the bottom layer of the first grain load due to a good weather condition during the drying period.

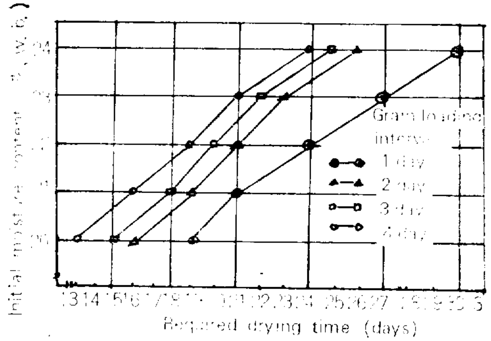
The earlier harvest begins, the less the harvest losses. However, higher initial moisture content of the grain requires more airflow rate, longer drying time, and causes a deterioration of the grain. With the consideration of economical and effective management for natural air layer drying systems, initial moisture content of the grain would not exceed 23% (w.b.) as much as possible.

B. Effect of Grain Loading Interval

The loading rate of the grain is a critical factor in layer drying systems. It is a function of both the amount of the grain added on a specifie date (load size) and the number of days between loading dates (load interval).

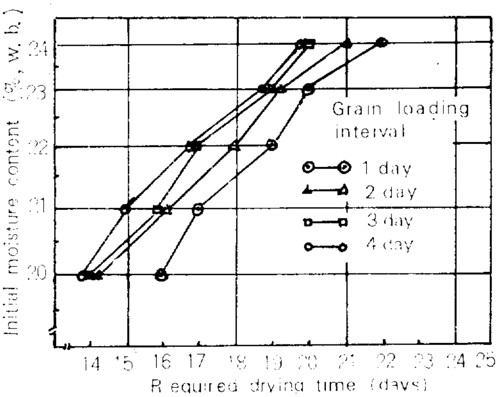
In this study, the grain loading interval from 1 to 4 days was considered and grain loading size was restricted to 0.5m in the bin depth.

Fig. 6 shows the relationship between the required drying time and the initial moisture content for various grain loading intervals when the intermittent fan operation was applied. The drying time was significantly reduced by increasing the grain loading interval. This indicates that, in the harvesting season, the daily reduction of the grain moisture in the field is greater than that in the grain bin during a daytime.



Note; Grain bin depth : 1.5m(0.5, 1.0, 1.5m)
Grain bin diameter : 2.0m
Airflow rate : 10.5, 5.0, 3.2cmm/m³
Fan operation : 9 : 00 AM—6 : 00 PM
(9 hours per day)

Fig. 6. Relationship between the required drying time and initial moisture content for various grain loading intervals.



Note; Grain bin depth : 1.5m(0.5, 1.0, 1.5m)
Grain bin diameter : 2.0m
Airflow rate : 10.5, 5.0, 3.2cmm/m³
Fan operation : 24 hours per day
(continuous)

Fig. 7. Relationship between the required drying time and initial moisture content for various grain loading intervals.

In case of the continuous fan operation, the relationship is shown in Fig. 7. Drying period was shorter compared to that for the intermittent fan operation but was not greatly influenced by the increase in the grain loading interval.

In the layer drying system, the grain loading interval should be within 5 days because an optimum harvest period is considered as about 15 days. Therefore, the grain loading interval from 2 to 4 days would be practical except bad weather conditions.

C. Effect of Fan Operation Method

The fan operation method is closely related to the energy cost for drying. Continuous fan operation decreases somewhat the drying period but leads to higher energy input for drying than intermittent fan operation due to the increased hours of fan operation.

Drying time was longer for the intermittent operation than for continuous operation regardless of grain loading intervals, but when the initial moisture content of the grain was 21 and 20% (w.b.) respectively, there was no significant difference between the intermittent and continuous fan operations. This result illustrates that for the continuous operation the grain at the bottom of the bin absorbs the water due to high humidity of the air at midnight and results in the delay of the drying process.

As a result, the intermittent fan operation provides reduction in the energy cost for drying but delays drying for higher initial moisture content above 22% (w.b.).

Summary and Conclusions

Experimental results on in-bin drying of rough rice with natural air show that the weather conditions during the harvesting season in Korea have good drying potential for low temperature drying system. Simulation model for the natural air drying system developed also reveals the possibility of adapting the natural air drying system of rough rice in Korea. However, all the experiments which have done so far were about full-bin drying. In addition, since new high yielding rice variety characterized by high shattering loss was introduced into Korea in 1969, and the mechanization of rice harvesting system was gradually transformed from the traditional and binder harvesting systems to combine harvesting system, early cutting and wet threshing for higher moisture content of rough rice are needed to reduce the grain losses during the harvesting operation.

Layer drying has long been recongnized as a means of increasing the drying potential of low temperature systems. Harvesting schedule with combine can also be controlled if layer drying is adapted.

The purpose of this study was to develop a simulation model for the layer drying of rough rice with natural air using average weather data in Suweon area during last 7 years(1973-1979), and to analyze effects of the variables on the layer drying system.

The results obtained are summarized as follows;

(1) The computer simulation model developed was validated with actual experiment, and was applicable to the natural air layer drying of rough rice.

(2) At the same initial moisture content of the grain, drying proceeded faster in layer drying than in full-bin drying.

(3) The high initial moisture content caused the grain deterioration at the top layer of the grain in the full-bin drying system. However, the layer drying would prevent the deterioration of the grain with high initial moisture content.

(4) In the layer drying system, drying period was longer in the intermittent fan operation method than in the continuous fan operation regardless of the drying methods. Since shorter fan operation time was required in the intermittent fan operation method, however, energy cost was also less in the intermittent method compared to the continuous fan operation method.

(5) In case of the intermittent fan operation method in which the fan was operated from 9 : 00AM to 6 : 00PM, the drying time was significantly reduced by increasing the grain loading interval in layer drying.

(6) When the initial moisture content is low (less than 21%), there was no significant difference in the drying time between the intermittent and continuous fan operation methods.

(7) Final grain moisture content at each load was approximately equal in all cases and was not affected by initial grain moisture content. However, overdrying occurred in the first grain load.

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