Drying Characteristics of Rough Rice in Continuous Dryer

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ABSTRACT

A drying model to predict the drying process in continuous dryer was developed and proved by drying experiments. The experiment showed that the difference of moisture contents between the predicted and the observed was within 0.5%(wb). There was no cracked rice found even in high drying rate with the inlet moisture content over 23%(wb), and tempering treatment in the same temperature reduced the ratio of cracked rice. There was a little difference in the ratio of cracked rice between 40℃ and 45℃ drying temperatures with the final drying moisture content(14.5% wb), and the cracked rice increased at 55℃. As a result, it was better to make fast drying on the rice over 23%(wb) inlet moisture content at about 55℃, and below the 23%(wb) inlet moisture content it was recommended to keep drying at 45℃.

Keywords : drying, drying model, continuous dryer, simulation.

INTRODUCTION

It has been considered as difficult to dry large amount of rice right after harvested for proper milling or storage. In Korea drying rice is being done by natural solar heat and by grain dryers. Only 20% is dried by dryers, and most of rice drying is still done by the solar energy.

About 100 RPC's(Rice Processing Complex) were constructed last 4 years in Korea to handle harvested rice more effectively for drying, storage, and milling.

The RPC's were mainly intended to reduce the production cost and to improve the rice quality by the proper drying processes. The drying method in RPC's is the complex drying method using both heated air and natural air in the small dryers of circulation type. The circulation type dryer is not appropriate in drying large amount of rice, because it has the low capacity and the drying process cannot be carried out smoothly. A continuous type of dryer is adquate to dry large amount of rice at a short time. The continuous dryers are not installed yet in domestic RPC's and need to be studied for the RPC usage.

Therefore, the objective of this study is to examine the characteristics of rice drying in continuous type of dryer. To do this, a drying model using the continuous type of dryer will be developed and validated by experiments in this study.

MATERIALS AND METHOD

1. Drying model

To predict drying process of the continuous dryer, a partial differential equation was defined with respect to the energy and mass balance in a control volume on a stationary bed under assumptions as belows;

- The temperature gradients within the individual rough rices are negligible.
- The rough rice-to-rice conduction is negligible.
- The airflow and grain flow are plug types and constant.
- The terms $\frac{\partial T}{\partial t}$ and $\frac{\partial w}{\partial t}$ are negligible compared with $\frac{\partial T}{\partial x}$ and $\frac{\partial T}{\partial x}$.
- The dryer wall is adiabatic with negligible heat capacity.
- The heat capacities of moist air and grain are constant during short time period.
- The single rough rice drying equation and the moisture equilibrium equation are accurate.
- The moisture evaporation takes place at the drying air temperature.

1) Mass balance on water vapor in solid phase

Mass balance equation during Δt is

$$\int_{t_i}^{t_i+\Delta t}[\mathit{input\ mass\ per\ unit\ time}-\mathit{output\ mass\ per\ unit\ time}]\cdot dt=$$

$$\int_{x_i}^{x_i+\Delta x}[\mathit{mass\ of\ system}\,|_{\,t_i+\Delta t}-\mathit{mass\ of\ system}\,|_{\,t_i}]\cdot dx$$

and each terms can be written in mass balance equation when

input mass per unit time is 0.

output mass per unit time $= \int_{x_i}^{x_i+\Delta x} A\cdot(1-\varepsilon)\cdot\gamma_{sw}(x_i,t_i)\cdot dx$

mass of system at t_i $= \rho\cdot A\cdot(1-\varepsilon)\cdot\overline{M}(x_i,t_i)$

mass of system at $t_i+\Delta t$ $= \rho\cdot A\cdot(1-\varepsilon)\cdot\overline{M}(x_i,t_i+\Delta t)$

Above equations are substituted in mass balance equation and arranged using mean value theorem of integral. The mass balance euqation on water vapor in solid phase is written

$$-\gamma_{sw}(x_i, t_i) = \frac{\rho}{\Delta t}\cdot\left[\,\overline{M}(x_i, t_i+\Delta t)\mid_{x_i+\beta_1\cdot\Delta x} - \overline{M}(x_i, t_i)\mid_{x_i+\beta_1\cdot\Delta x}\right]$$

and now taking $\Delta x \to 0$, $\Delta t \to 0$, the equation is rearranged as

$$\frac{\partial \overline{M}}{\partial t} = -\frac{\gamma_{sw}}{\rho}$$

2) Mass balance on water vapor in air phase

The mass balance equation on water vapor in air phase is

$$\int_{t_i}^{t_i+\Delta t}[\text{input water vapor per unit time} - \text{output water vapor per unit time}]\cdot dt$$

$$= \text{amount of water vapor at } t_i+\Delta t - \text{amount of water vapor at } t_i$$

Each term can be written as

input water vapor per unit time

$$= G_a\cdot A\cdot w(x_i, t_i)\cdot dt + \int_{x_i}^{x_i+\Delta x}\gamma_{sw}(x_i, t_i)\cdot A\cdot(1-\varepsilon)\cdot dx$$

output water vapor per unit time = $Ga\cdot A\cdot w(x_i+\Delta x, t_i)\cdot dt$

amount of water vapor in system at $t_i+\Delta t$ = $\rho_a\cdot\varepsilon\cdot A\cdot w(x_i, t_i+\Delta t)\cdot dx$

amount of water vapor in system at t_i = $\rho_a\cdot\varepsilon\cdot A\cdot w(x_i, t_i)\cdot dx$

Above equations are substituted in mass balance equation and arranged using mean value theorem of integral and taking $\Delta x \to 0$, $\Delta t \to 0$. The equation is written as

$$\frac{\partial w}{\partial x} = -\frac{\rho_p}{G_a}\cdot\frac{\partial \overline{M}}{\partial t}$$

3) Energy balance on air phase

The energy balance equation on air phase is

$$\int_{t_i}^{t_i+\Delta t}[\mathit{input\ energy\ per\ unit\ time} - \mathit{output\ energy\ per\ unit\ time}]\cdot dt$$

$$= \int_{x_i}^{x_i+\Delta x}\text{amount of enthalpy in system [at } t_i+\Delta t - \text{ at } t_i]\cdot dx$$

Each term can be written in energy balance equation as

input energy per unit time $= G_a\cdot A\cdot H_a(x_i, t_i) + G_a\cdot A\cdot w(x_i, t_i)\cdot H_w(x_i, t_i)$

$$+\int_{x_i}^{x_i+\Delta x}A\cdot(1-\varepsilon)\cdot H_w(x_i, t_i)\cdot\gamma_{sw}(x_i, t_i)\cdot dx$$

output energy per unit time $= G_a\cdot A\cdot H_a(x_i+\Delta x, t_i) + G_a\cdot A\cdot w(x_i+\Delta x, t_i)\cdot H_w(x_i+\Delta x, t_i)$

$$+\int_{x_i}^{x_i+\Delta x}h\cdot a\cdot A\cdot[\,T(x_i, t_i) - \theta(x_i, t_i)]\cdot dx$$

amount of enthalpy in system at ti $= A\cdot\varepsilon\cdot[\rho_a\cdot H_a(x_i, t_i) + \rho_a\cdot H_w(x_i, t_i)\cdot w(x_i, t_i)]\cdot dx$

amount of enthalpy in system at ti + Δt

$$= A \cdot \varepsilon \cdot [\rho_a \cdot H_a(x_i, t_i+\Delta t) + \rho_a \cdot H_w(x_i, t_i+\Delta t) \cdot w(x_i, t_i+\Delta t)] \cdot dx$$

Above equations are substituted in energy balance equation and arranged using mean value theorem of integral and taking Δx→0, Δt→0. The equation is written as

$$\frac{\partial T}{\partial x} = -\frac{h \cdot a \cdot (T-\theta)}{G_a \cdot c_a + G_a \cdot c_v \cdot w}$$

4) Energy balance on solid phase

The energy balance equation on air phase is

$$\int_{t_i}^{t_i+\Delta t} [\textit{input energy per unit time} - \textit{output energy per unit time}] \cdot dt$$

$$= \int_{x_i}^{x_i+\Delta x} \text{amount of enthalpy in system [at } t_i+\Delta t \text{ - at } t_i] \cdot dx$$

Each term can be written in energy balance equation as

input energy per unit time $= \int_{x_i}^{x_i+\Delta x} h \cdot a \cdot A \cdot [T(x_i, t_i) - \theta(x_i, t_i)] \cdot dx$

output energy per unit time $= \int_{x_i}^{x_i+\Delta x} A \cdot (1-\varepsilon) \cdot H_w(x_i, t_i) \cdot \gamma_{sw}(x_i, t_i) \cdot dx$

amount of enthalpy in system at ti $= A \cdot [\rho_p \cdot h_d(x_i, t_i) + \rho_p \cdot \overline{M}(x_i, t_i) \cdot h_w(x_i, t_i)]$

amount of enthalpy in system at ti+Δt

$$= A \cdot [\rho_p \cdot h_d(x_i, t_i+\Delta t) + \rho_p \cdot \overline{M}(x_i, t_i+\Delta t) \cdot h_w(x_i, t_i+\Delta t)]$$

Above equations are substituted in energy balance equation and arranged using mean value theorem of integral and taking Δx→0, Δt→0. The equation is written as

$$\frac{\partial \theta}{\partial t} = \frac{h \cdot a \cdot (T-\theta)}{\rho_p \cdot (c_p + \overline{M} \cdot c_w)} - \frac{h_{fg} + c_v \cdot (T-\theta)}{\rho_p \cdot (c_p + \overline{M} \cdot c_w)} \cdot G_a \cdot \frac{\partial w}{\partial x}$$

Now the above four equations are arranged to apply the continuous drying model.

In the stationary bed model, the time term Δt can be replaced as

$$\Delta t = \frac{\Delta y}{V_p}$$

$$dt = \frac{dy}{V_p}$$

and also

$$G_p = V_p \cdot \rho_p$$

Finally the equation of continuous drying model can be described as belows

$$\frac{\partial w}{\partial x} = -\frac{G_p}{G_a} \cdot \frac{\partial \overline{M}}{\partial y}$$

$$\frac{\partial T}{\partial x} = -\frac{h \cdot a \cdot (T-\theta)}{G_a \cdot c_a + G_a \cdot c_v \cdot w}$$

$$\frac{\partial \theta}{\partial y} = \frac{h \cdot a \cdot (T-\theta)}{G_p \cdot (c_p + \overline{M} \cdot c_w)} - \frac{h_{fg} + c_v \cdot (T-\theta)}{G_p \cdot (c_p + \overline{M} \cdot c_w)} \cdot G_a \cdot \frac{\partial w}{\partial x}$$

$$\frac{d\overline{M}}{dt} = \text{appropriate thin layer equation}$$

2. Solution of drying model

The four equations of drying model can be solved by use of finite difference method(Von rosenberg). The simplified solutions are expressed

$$\overline{M}_{new} = \frac{\overline{M}_{old} - \Delta t \cdot K_{old} \cdot M_e}{1 - \Delta t \cdot K_{old}}$$

$$W_{new} = W_{old} + 2\Delta x \cdot \left(-\frac{G_p}{G_a} \cdot \frac{\overline{M}_{new} - \overline{M}_{old}}{\Delta y} \right)$$

$$\theta_{new} = \frac{1 - C_4}{1 - C_4 + 2C_3} \cdot \left(\theta_{old} + \frac{2C_3}{1 - C_4} \cdot T_{old} - 2C_1 \cdot C_2 \cdot h_{fg} \right)$$

$$T_{new} = \frac{1}{1 - C_4} \cdot [(1 + C_4) \cdot T_{old} - 2C_4 \cdot \theta_{new}]$$

Using a personal computer, a program to solve the moisture content of grain($\overline{M}$), absolute humidity of drying air(W), grain temperature(θ) and drying air temperature(T) at any point of control volume was made.

3. Drying Experiment

1) Experimental Apparatus

The continuous type of dryer used for this experiment was a cascade type, in which grains were dried while moving on the perporated plate. A petroleum heater and two pairs of cartridge heater were used to heat the driven air. The specification and diagram of the dryer are as shown in Table 1 and Figure 1.

2) Raw Material

Variety of rice used for the experiment was "Chosangjong", which was harvested on Sep 18 in 1996 in Jinchon, Choongbook.

3) Measuring Moisture Content

10g samples were used to measure moisture contents after drying by oven method(135℃ -24hrs)

4) Measuring the ratio of cracked rice

The sample was exposed in the natural air for 72 hours after dried, and the ratio was measured by a test-huller and a single grain rice inspector using photo sensor and halogen light.

5) Standard Sample

A 10-kg sample of 23%(wb) initial moisture content was dried to 15%(wb) at average drying rate of 0.17%/hr by the natural air.

6) Tempering treatment

The sample was exposed in the natural air after dried for 24 hours. Its temperature was made equal to that of the atmosphere.

7) Experimental Condition

The experiment was conducted under the condition in Table 2.

RESULT AND DISCUSSION

Table 3 is shown the experimental results at each experimental conditions.

1. Validation of the drying model

The measured moisture contents were compared with the predicted values. The results are shown in Table 3 and Figure 2. Regression analysis is shown in Figure 3. Comparison results of drying air temperature, relative humidity, output grain temperature at special points in control volume are shown in Table 4, Figure 4, Figure 5 and Figure 6.

As shown in Table 3, the difference of output moisture content between the predicted and the measured was below 0.5%(wb). As the regression result was shown in Figure 3, the predicted value was nearly concordant with the measured value. Also the predicred values of drying air temperature and output grain temperature were almost the same as the measured. However, in case of drying air relative humidity, the big difference between the predicted and the experimental value is resulted from that the humidity sensor was affected by the ambient air surrounded sensor as the measuring point of humidity sensor was located around 5cm above from the top of the drying bed.

As the comparison results of the predicted and the measured for the output moisture content, drying air temperature and output grain temperature, it would be expected that the developed drying model could be functioned to explain the continuous drying process with precisely.

2. Drying temperature affection causing cracked rice during the drying process

To figure out the effect of drying air temperature to cause cracked rice, the experiments 1, 2 and 12 were performed under the drying air temperature 40℃, 45℃, 55℃ respectively.

Comparing with the 14% level of ouput moisture content, the ratio of cracked rice was occured equally, 14.61% and 14.54%, in case of 40℃ and 45℃ of drying air temperature respectively. However, it was taken place at slightly above 55℃ of drying temperature. Through the all cases of experiment, the ratio of cracked rice was recorded around 5% compared with the below 19%(wb) of output moisture content.

Considering with the results of the experiment, the drying rate could be selected over 3%(wb)/hr when input moisture content was above 23%(wb).

3. Tempering treatment affection causing cracked rice during the drying process

It will be expected that the tempering treatment reduce the cracked rice effectively as the results of experiment 7 and 1. Because the output moisture content was not the same between two experiments, it is difficult to compare directly. However, indirectly comparing the occuring current of the ratio of cracked rice, the value of experiment 1 was more higher than that of experiment 7.

CONCLUSIONS

A drying model to predict of drying process for domestic industrilizition of the continuous dryer was developed and validated the drying model through experiments.

As the results of experiment, the following conclusions were drawn;

1) Developed drying model was able to predict the drying process precisely and the moisture content difference was within 0.5%(wb).

2) Under the input moisture content of above 23%(wb) and drying air temperature ranged 40℃~55℃, the drying air temperature did not affect the ratio of cracked rice.

3) The tempering treatment effectively reduced the ratio of cracked rice and so it was inevitable equipment for a continuous drying system.

NOMENCLATURES

γ_{sw} : rate of water vapor transferred per unit time per unit volume of grain(kg - H_2O/hr · m^3)
A : cross sectional area of control volume (m^2)
ρ : true density of dry grain (kg/m^3)
ε : porosity of control volume (decimal)
$\overline{M}(x_i, t_i)$: mean moisture content of grain (decimal, db)
G_a : mass flow rate of dry air (kg - dry air/hr · m^2)
ρ_a : density of dry air (kg - dry air/m^3)
ρ_p : bulk density of dry grain (kg/m^3)
$w(x_i, t_i)$: absolute humidity of air (kg - H_2O/kg - dry air)
Hw : enthalpy of moist in air (kJ/kg)
Ha : enthalpy of dry air (kJ/kg)
h : convective heat transfer coefficient (kJ/hr · m^2 · ℃)
a : particle surface area per unit control volume (m^2/m^3)
$T(x_i, t_i)$: drying air temperature (℃)
$\theta(x_i, t_i)$: grain temperature (℃)
$c_a = \frac{\partial H_a}{\partial T}$ (kJ/kg · ℃) : specific heat of dry air
$c_v = \frac{\partial H_w}{\partial T}$ (kJ/kg · ℃) : specific heat of water vapor
h_w : enthalpy of water in grain (kJ/kg)
h_d : enthalpy of dried grain (kJ/kg)
$c_p = \frac{\partial h_d}{\partial \theta}$ (kJ/kg · ℃) : specific heat of dry grain
$c_w = \frac{\partial h_w}{\partial \theta}$ (kJ/kg · ℃) : specific heat of liquid water
h_{fg} : heat of evaporation (kJ/kg)
Vp : grain flow rate (kg-grain/hr)

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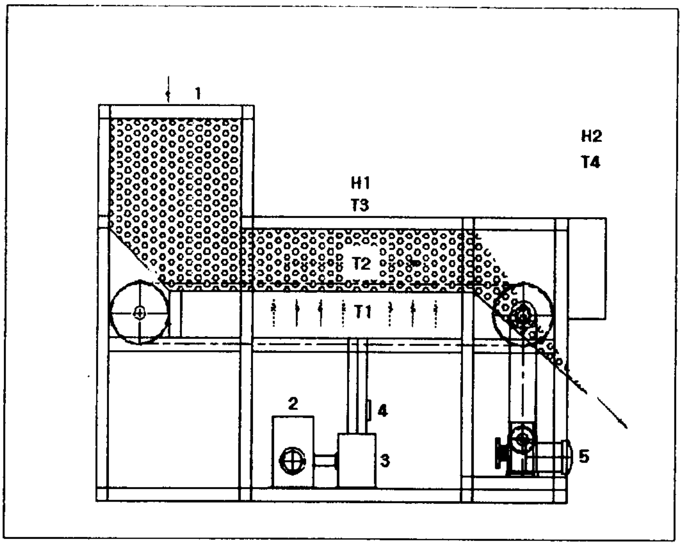

Fig. 1. Schematic diagram of experimental apparatus for a continuous rice drying.

Table 1. Specifications of experimental apparatus.

Symbol	Description	Specification
1	Continuous dryer	90(kg/hr)
2	Main heater	4000(kcal/hr)
3	Fan	10(m^3/min)
4	Catridge heater	400(W) X 6EA
5	Geared motor	0.4(Kw)
T1	Temperature sensor	Pt-100
T2	Temperature sensor	Pt-100
T3	Temperature sensor	Pt-100
T4	Temperature sensor	Pt-100
H1	Humidity sensor	Elec. resistance type
H2	Humidity sensor	Elec. resistance type

Table 2. Experimental conditions of the continuous rice drying.

Exp. No.	Airflow rate ($m^3/s \cdot ton$)	Mov. speed (hr/pass)	Drying air temp. (℃)	Amb. air temp. (℃)	Amb. air RH. (%)	Input grain temp. (℃)	Input MC. (%,wb)
1-1	2.5	0.554	45.49	22.94	66	24.1	22.44
1-2	2.5	0.554	45.28	23.88	78	33.1	19.3
1-3	2.5	0.554	45.17	21.17	71.6	34.7	17.03
1-4	2.5	0.554	44.77	20.84	73	35.7	14.84
2-1	2.5	0.554	54.98	22.22	49	24.2	23.7
2-2	2.5	0.554	54.28	22.93	48	38.2	18.62
12-1	2.5	0.554	39.9	22.05	49	20	22.06
12-2	2.5	0.554	40.3	21.31	49	30.3	18.82
12-3	2.5	0.554	40.15	19.45	51	32.8	16.21
5-1	2.5	0.675	44.85	24.21	66	15.5	22.49
5-2	2.5	0.675	45.02	23.73	62	33.8	18.48
6-1	2.5	0.335	45.17	23.64	70	14.5	22.42
6-2	2.5	0.335	44.97	24.21	67	32.5	19.98
6-3	2.5	0.335	45	23.4	75	34.3	17.92
7-1	2.5	0.554	44.81	21.98	74	18.8	25.16
7-2	2.5	0.554	44.93	23.2	77	23.1	21.16
7-3	2.5	0.554	44.93	23	75	23.2	17.86
std-15	Natural air drying for standard sample						
std-16	Natural air drying for standard sample						

Table 3. Experimental result of the continuous rice drying.

Exp. No.	Airflow rate (m^3/ s · ton)	Mov. speed (hr/ pass)	Drying temp. (℃)	Amb. air temp. (℃)	Amb. air RH. (%)	Input grain temp. (℃)	Cracked rice ratio (%)	Input MC. (%,wb)	Out MC. (%,wb)	
									Pre.	Exp.
1-1	2.5	0.554	45.49	22.94	66	24.1	2.06	22.44	19.42	19.2
1-2	2.5	0.554	45.28	23.88	78	33.1	5.12	19.3	16.75	17.17
1-3	2.5	0.554	45.17	21.17	71.6	34.7	14.54	17.03	14.64	14.59
1-4	2.5	0.554	44.77	20.84	73	35.7	17.96	14.84	12.87	13.18
2-1	2.5	0.554	54.98	22.22	49	24.2	2.68	23.7	19.49	19.17
2-2	2.5	0.554	54.28	22.93	48	38.2	11.8	18.62	15.05	15.56
12-1	2.5	0.554	39.9	22.05	49	20	5.24	22.06	19.39	19.5
12-2	2.5	0.554	40.3	21.31	49	30.3	10.96	18.82	16.34	16.59
12-3	2.5	0.554	40.15	19.45	51	32.8	14.61	16.21	14.07	14.53
5-1	2.5	0.675	44.85	24.21	66	15.5	3.83	22.49	19.13	18.87
5-2	2.5	0.675	45.02	23.73	62	33.8	10.08	18.48	15.44	16.28
6-1	2.5	0.335	45.17	23.64	70	14.5	2.16	22.42	20.66	20.46
6-2	2.5	0.335	44.97	24.21	67	32.5	4.06	19.98	18.21	17.85
6-3	2.5	0.335	45	23.4	75	34.3	8.36	17.92	16.34	16.07
7-1	2.5	0.554	44.81	21.98	74	18.8	3.55	25.16	22.15	21.57
7-2	2.5	0.554	44.93	23.2	77	23.1	5.46	21.16	18.47	18.27
7-3	2.5	0.554	44.93	23	75	23.2	10.4	17.86	15.55	15.5
std-15							4.23			
std-16							4.42			

Table 4. Experimental result of the continuous rice drying.

Exp. No.	Drying air temp.(℃)		Grain temp.(℃)		Drying air RH.(%)	
	Pre.	Exp.	Pre.	Exp.	Pre.	Exp.
1-1	37.48	42.55	39.87	37.90	80.84	99.00
1-2	43.10	42.76	41.01	40.20	69.26	68.11
1-3	43.27	41.84	41.40	39.00	55.51	40.97
1-4	43.26	42.46	41.75	40.90	46.93	30.51
2-1	50.92	45.72	47.08	45.20	72.64	99.00
2-2	51.41	49.88	48.59	48.10	49.19	33.38
12-1	37.28	35.75	34.96	35.70	81.83	85.77
12-2	38.22	37.59	36.28	36.70	64.78	39.06
12-3	38.48	38.32	36.87	36.20	52.08	32.92
5-1	42.21	40.88	39.75	38.90	79.85	99.00
5-2	43.05	42.45	41.12	40.40	59.45	40.20
6-1	41.72	34.40	38.81	36.00	91.86	99.00
6-2	42.13	38.95	39.59	38.20	78.05	85.20
6-3	42.65	40.34	40.46	39.20	68.55	73.80
7-1	41.26	38.93	38.43	37.00	94.90	99.00
7-2	42.38	41.08	40.01	40.10	77.90	98.5
7-3	42.97	42.13	41.05	40.70	62.25	66.20

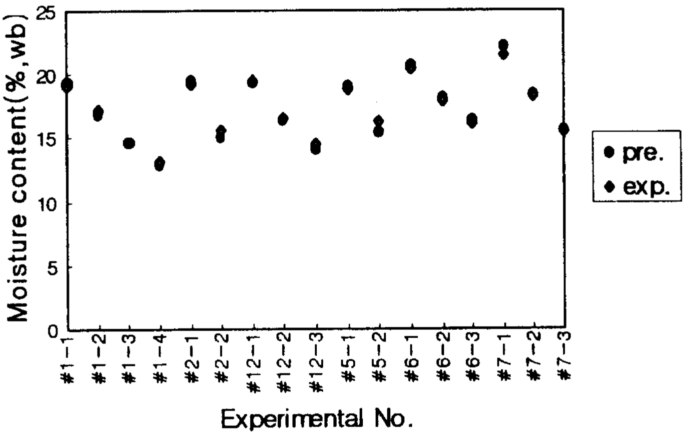

Fig. 2. Comparison of moisture content of the predicted and the measured values.

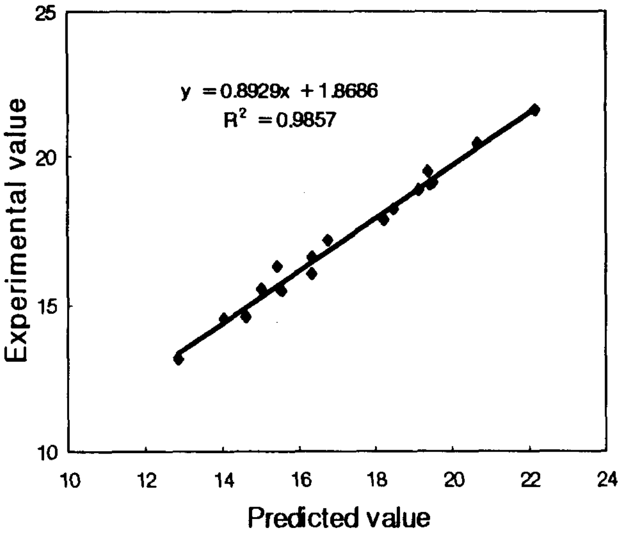

Fig. 3. Moisture content regression for the predicted vs. the measured values.

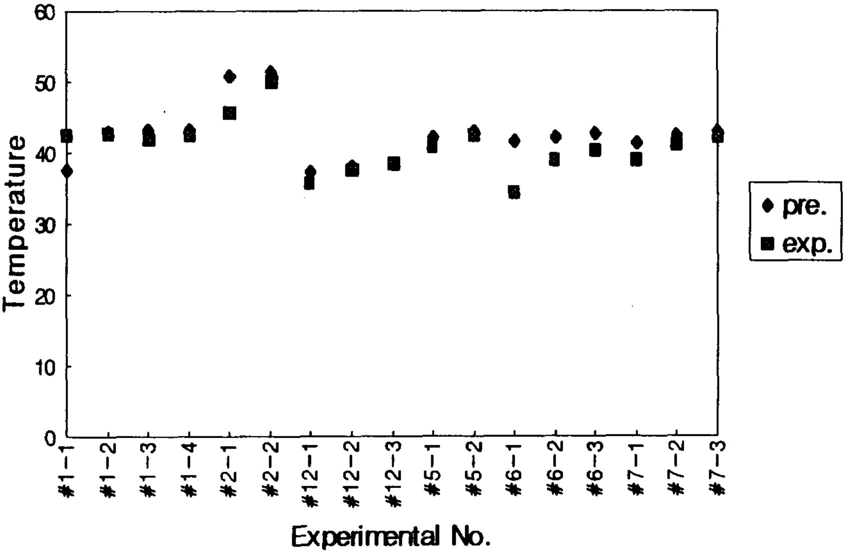

Fig. 4. Comparison of drying air temperature of the predicted and the measured values.

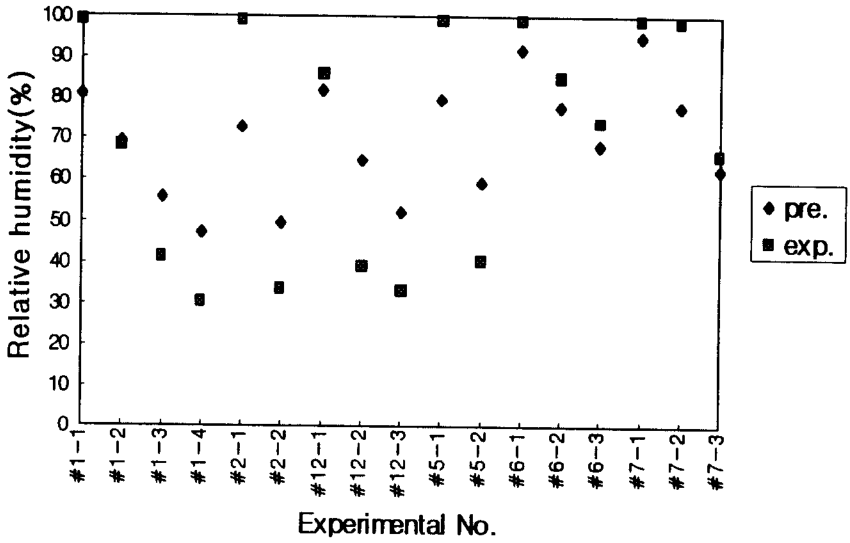

Fig. 5. Comparison of relative humidity of the predicted and the measured values.

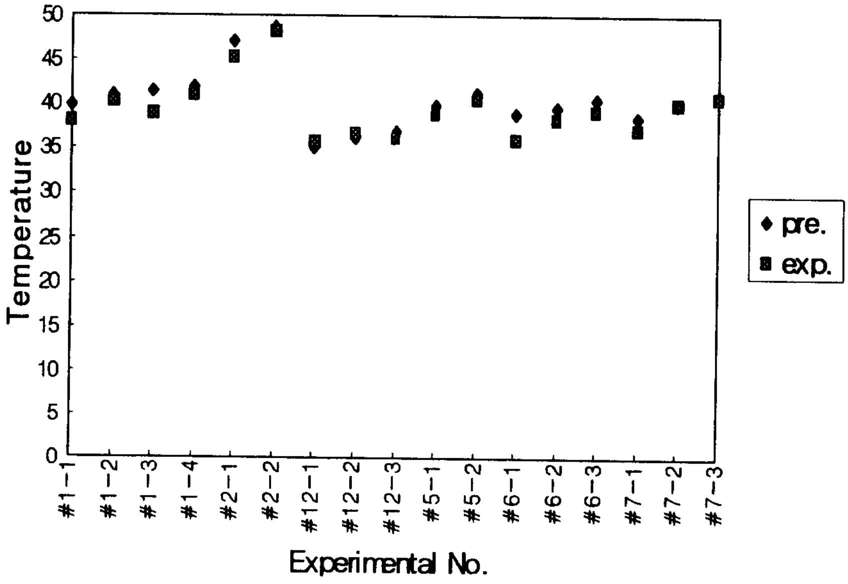

Fig. 6. Comparison of grain temparature of the predicted and the measured values.