벼의 압력손실 및 호흡 모델과 자동통풍에 관한 연구

PRESSURE DROP, RESPIRATION MODELS AND AUTOMATIC AERATION OF ROUGH RICE

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적 요

빈 시스템에서 적정 팬을 선정하기 위해서, 빈에서 벼를 건조 혹은 통풍시킬 때 벼의 저항에 의해 발생되는 공기의 압력손실을 예측하는 모델을 개발하였다. 또한 벼의 건물 손실을 예측하기 위하여 벼의 호흡 모델을 개발하였다. 그리고 온도 및 습도 센서들을 이용한 자동계측 시스템을 사용하여 저장된 벼의 상태를 연속적으로 측정, 분석함으로써 벼의 통풍기준을 결정하고 이를 근거로 빈의 자동통풍 시스템을 개발하여 평가하였다. 공기의 정압 손실은 공기의 속도 및 벼의 함수율의 함수로서 나타내어 졌으며, 일정 곡물 깊이에서 벼의 함수율이 낮을수록 그 정압손실은 증가하였다. 벼의 호흡에 의해 발생되는 이산화탄소의 양은 저장온도, 벼의 함수율, 저장 기간의 함수로서 나타낼 수 있었다. 벼의 안전 저장을 위해 곡물의 온도 및 함수율, 평형상대습도, 벼의 품질저하지수(deterioration index)에 대한 자동통풍 기준을 결정하였으며 이들을 이용해서 퍼스널 컴퓨터로 팬, 제습기 등의 통풍 장치들을 자동제어하는 자동통풍 시스템을 개발하였다. 이 시스템은 곡물의 상태를 예측, 제어함으로써 14% 이하의 함수율과 4이하의 품질저하지수, 그리고 어떤 균류도 생성시키지 않음으로써 벼를 안전하게 저장할 수 있었다.

I. INTRODUCTION

The major problem during storage of rice is the in situ measurement of its moisture content. Rice moisture content, inter granular air temperature and relative humidity, and carbon dioxide level are important factors in determining rice quality. Because these conditions are continuously changing throughout the rice mass during storage, a continuous monitoring and control system is required for automatic aeration of stored rough rice. Improved moisture models are necessary to measure in situ rice moisture content with electrical sensors. An accurate static pressure drop model, respiration model, and an automatic aeration system also need to be developed for maintaining low moisture and preventing spoilage, and optimum storage of

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rough rice.

One of the bases of the design of grain aeration systems is the expected static pressure drop. An accurate static pressure drop model is required for the determination of the power required for the aeration fan. It has been reported that the resistance to airflow in rough rice is affected by parameters such as air velocity, rice moisture content, and fine materials(Siebenmorgen and Jindal, 1987). Hence, the effects of air velocity, rice moisture, and air temperature on the static pressure drop during rice aeration and drying should be further investigated.

In addition, it is essential to maintain the grain quality during storage to minimize losses. Quality losses of grains occur because of grain and mold respiration. It is therefore necessary to develop an accurate respiration model for rough rice in order to determine the proper and necessary aeration practices during rice storage. Some researchers have reported models of dry matter loss of rough rice based on the carbon dioxide and the heat produced by the respiration of rough rice(Seib et al., 1980, Murata et al., 1976, and Teter, 1981). However, the dry matter losses predicted by their models were inconsistent.

Aeration is the most widely used environmental control method for the preservation of grain in storage.

Brooks (1950) reported that the suitability of the air for aeration could be assessed by analyzing the deterioration index(DI) of air. The DI was defined as follows :

$$DI = (IARH - 65.0) * PAS/10000$$

where, IARH = inital air rel. humidity(%)

$$PAS = \exp(X/Y + 16.91134)$$

$$X = -27405.526 + (TA * 97.5413) - (0.146244 * TA^2) + (0.00012558 * TA^3) - (0.48502E-0.7 * TA^4)$$

$$Y = 4.34903 * TA - 0.3938E-02 * TA^2$$

$$TA = IATEMP + 273.96$$

IATEMP = initial air temperature, ℃

An automatic control system of aeration provides a more accurate and consistent environmental control than a manual control. Zhang et al. (1986) developed a grain storage control system based on temperature, moisture content, and carbon dioxide measurements. This system could not accurately predict the precise grain conditions of moisture content and temperature at various locations because they were calculated by a simulation model using the statistical weather data. Rice conditions at a certain location in a bin are affected by ambient and intergranular air conditions. Large gradients in moisture content and temperature of rough rice can possibly exist and cause spoilage without being detected. Hot spots and moisture gradients in a bin should be detected before spoilage occurs by a continuous monitoring system with a real time model. An automatic aeration system should be used to control this situation.

A study was therefore undertaken on the a static pressure drop model, a respiration model, aeration control criteria, and personal computer based aeration system using a continuous monitoring system. The specific objectives were :

1) to develop a pressure drop model of air through rough rice for selection a proper fan in aeration of rough rice,

2) to develop a respiration model of rough rice to determine dry matter loss during rice storage,

3) to determine control criteria for rice aeration and to develop a PC-based automatic aeration system that continuosly monitors and controls grain and air conditions for safe storage of rough rice, and to evaluate the developed auto-

matic aeration system.

II. MATERIALS AND METHODS

2.1 Model Bin System

An experimental model bin was used for the development of a pressure drop model and automatic aeration of rough rice. The model bin system consisted of a storage chamber, an air conditioning unit, and an air flow measurement section. These sections were connected by insulated galvanized sheet metal ducts. The air conditioning unit (Parameter Generation Inc., Capacity : 8.4m^3/min.) supplied a continuous flow of conditioned air. This unit is capable of maintaining the temperature and relative humidity within 0.1℃ and 0.5%, RH, respectively.

A 1 m long aluminum duct with internal diameter of 14.95 cm was attached to the output side of the air conditioning unit. The aluminum duct was equipped with one damper to control air flow rate. A digital air flow meter (Model 29-DODC, OTA Keiki Inc.) was used for measuring air velocity of outlet air through rough rice. The 60 cm high test chamber was constructed with a 29.5 cm internal diameter PVC pipe. The bottom of this pipe was fitted with wire mesh to hold the grain. A series of 4 mm diameter holes was drilled on the wall of the bin chamber, and thermocouple probes and relative humidity sensors (Vaisala Inc., capacitance type) were inserted at the center of the bin chamber through the holes to measure and monitor temperature and relatire humidity of air. Additional holes of 2 cm diameter were also drilled to withdraw small samples from each of these layers for moisture determination. All electrical sensors were connected to a data acquisition system using a personal computer.

2.2 Pressure Drop Model of Rough Rich

A. Samples and Experimental Apparatus

Long grain rice of Tebonnet variety harvested during the 1987 season was stored in a refrigerator at 4℃. Initial moisture content of the rice used in these tests was 26 to 27% (w.b.). Samples harvested by a combine contained foreign materials of 0.9%. Samples were dried with ambient air in the laboratory to obtain required moisture content of rough rice for pressure drop tests.

Two rubber hoses connected to a differential pressure transducer (Model 221A, MKS Instruments Inc.) were inserted into the center of the bin chamber through the side holes to measure the pressure difference between the top and bottom layers located 30 cm apart. The rubber tubber tubes were placed horizontally to minimize the effect of air velocity on static pressure drop. The pressure transducer operated in the range of 0 to 100 mm of water with a resolution of 0.01 mm. Outputs of the transducer were read and acquisitioned by a digital readout (PDR-C-1B, MKS Instruments Inc.) and a data acquisition system (PC-ACQUISTOR, Dianachart Inc.). Pressure drop was expressed in Pascals per meter of rice depth (Pa/m).

B. Procedure

A stabilization period of half an hour was allowed for desired conditions of air temperature, relative humidity, and air velocity. The bin chamber was loosely filled with rough rice of 30 cm depth (about 0.0212 m^3) for each test. Rice moisture content was determined using an air oven method (110℃, 24 hours). Experiments were conducted at air velocities from 0.011 to 0.222 m^3/s/m^2 in increments of 0.011 m^3/s/m^2 at four rice moisture levels of 12.8%, 15.2%, 22.0%, 27.0% (w.b.) and air temperatures of 25℃ and 38

℃ The relative humidity of air in the tests was fixed at 50%. Air with temperature of 25℃ and relative humidity of 50% was selected to represent common conditions of late fall in south Louisiana. The level of air with 38℃ was selected for pressure drop tests because optimum drying temperature in Louisiana is 38℃. Experimental results of these tests were analyzed to investigate the effects of air velocity, rice moisture, and air temperature and to develop a pressure drop model of rough rice using regression analysis, SAS/STAT (1985).

2.3 Respiration Model of Rough Rice

Long grain rice of Tebonnet variety harvested during the 1988 season was stored in a refrigerator at 4℃. The initial moisture content of rough rice used for this experiment was about 23% and 27% (w.b.). The rough rice contained foreign materials of 0.9%.

Respiration of grain can be measured either in closed or in aerated(intermittent or continuous) systems. The closed system uses a static technique in which carbon dioxide produced after a fixed period is measured. The static method had great appeal because of its simplicity and also because it was assumed to duplicate conditions that exist in bulk storage (Pomeranz, 1982). Hence, a static method was used to investigate the effects of rice moisture, temperature, and foreign materials on the amount of carbon dioxide produced during storage of rough rice. The amount of carbon dioxide produced during storage of rough rice was measured with an aspirating pump(Model 400A, Kitagawa Inc.) and stain detector tubes (Figure 1). The stain detector tubes used were of three different types, SA, SB, and SH. Type SA was for the measuring range of 0.05 to 1.0%, type SB for the range of 0.1 to 2.6% and type SH for the range of 0 to 20%. The detectable limits of the each type were respectively 0.005%, 100 ppm and 0.1%. The volume of the detector tubes was 100 ml. A new tube was used for each measurement of the carbon dioxide.

Samples were stored for measuring the respiration of rough rice in sealed PVC barrels with a diameter of 0.286m and a depth of 0.356m (volume of 22.805 L). The size of the barrel was enough to supply the amount of oxygen required for respiration of the sample of 0.5 kg to 1kg. Each sample stored in a barrel had respectively a different storage condition. Samples with various moisture levels of 12.5, 13.5, 14.3, 15.0, 17.0, 19.0 23.3, 25.0, anel 27.0% were tested at air temperature of 20, 27, and 34℃.

The concentration (%) of carbon dioxide produced from the respiration of the stored rough rice was measured at different location (surface and middle layer of grain) of the barrel with an interval of time. The measured concentrations of carbon dioxide were used to investigate the effects of rice moisture and temperature on the respiration of rough rice. A mechanical damage level of rough rice was considered to be negligibly small.

The concentration (%) of carbon dioxide were expressed as mg of CO2 per 100 grams of dry matter to determine the dry matter loss (%) of rough rice. A respiration model of rough

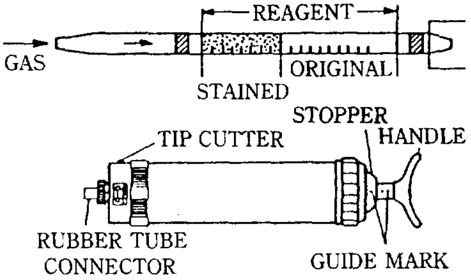


Fig 1. The aspirating pump and detector tube used for measurement of carbon dioxide.

rice was developed to predict the amount of carbon dioxide produced during storage of rough rice using the translated values (mg) of CO2.

2.4 PC-Based Automatic Aeration of Rough Rice.

The PC-based automatic aeration system consisted of knowledge of the control criteria and hardware of the aeration system such as electrical sensors, a continuous monitoring system with a personal computer (PC), an on-off control system, a fan, a heater, a dehumidifier, and a stirring device. Some control criteria for the automatic aeration system of rough rice were determined using the continuous monitoring system developed for stored rough rice (Chung, 1989). The aeration system using the control criteria was also later evaluated.

A. Control Criteria of Rice Aeration

Control criteria for rice aeration were determined based on i) temperatures of air and rice, ii) relative humidities of local air and ambient air, iii) rice moisture content, iv) dry matter loss of rice, and v) deterioration index. The continuous rough rice monitoring system using electrical sensors for temperature and moisture was used for determination of control criteria of rice aeration. Storage conditions of rough rice were recorded and monitored for several different trials, and data were analyzed to determine control criteria of rice aeration.

B. Hardware for Automatic Aeration System

The automatic aeration system consisted of four main parts : electrical sensors, a digital dfata acquisition system with a personal computer, an on-off control system with ten relays, and equipment required for aeration (figure 2). Temperature and humidity sensors of capacitance-type were used for ambient air and intergranular air, while copper-constantan thermocouples were used to measure rice temperature. A digital data acquisition system, 48-channel PC-ACQUISITOR (Dianachart, Inc.), was used to continuously record and monitor the conditions of air and grain. This had a measurement range from 0.3 micro volts up to 10 volts, 16 bit resolution, ± 0.02% accuracy of range, 11 on-off TTL inputs, 10 TTL outputs, and special functions of auto-calibration and auto-calibration and auto-amplification. It included hardware to measure the cold junction temperature for thermocouples, and to provide excitation to RTDs, strain gages, and pressure transducers. The PC-ACQUISITOR automatically adjusted its amplifier gain from input to input so as to make the most accurate measurement possible. A RO-Relay-Output (Dianachart Inc.) was used for control/alarm of the rice aeration system. It had 10 on-off relays and driver circuitry to operate high-level circuits from the TTL outputs of the PC-ACQUISITOR. Each output was a 2-pole double throw relay with contacts rated at 3A, 120V AC. The relays were of a plug-in type, and a LED status indicator was provided.

For aeration, an axial suction-fan (20 W) and a dehumidifier (Kenmore, Inc.) with water removal rate of 295.7 cm^3/hr were automatically controlled. A small stirrer (Sargent, Inc.) and an air conditioning unit were connected as auxiliary devices. A heater and a stirrer were, if required, together operated for short time by an alarm signal from the PC-ACQUISITOR. Fan power was calculated from static pressure drop of air, and airflow rate (0.016-0.804 cmm/m^3, Brooker et al., 1982) recommended for aeration of dried rough rice. Pressure drop of air through rough rice in the model bin was predicted by the pressure drop model of rough rice develo-

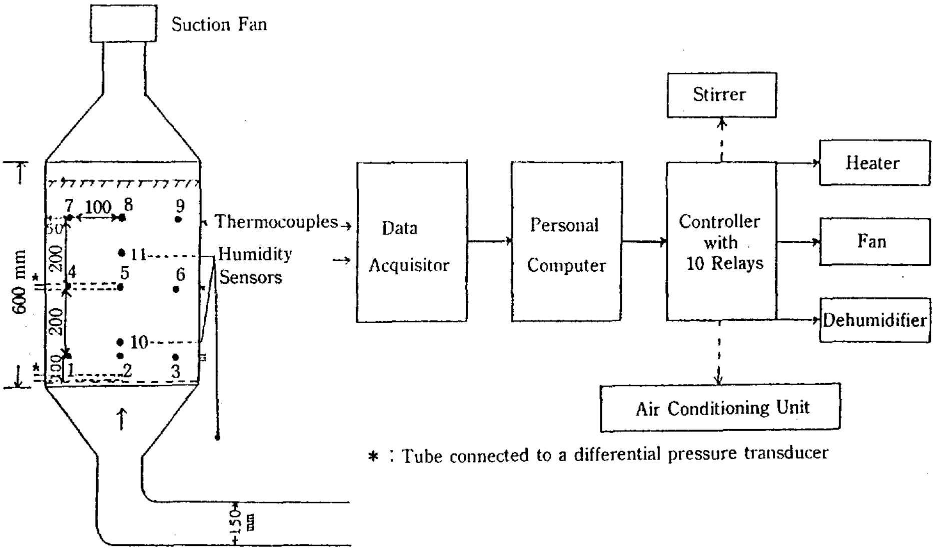


Fig 2. Automatic aeration system of rough rice

ped in the previous section.

C. Software for Automatic Aeration System

A menu-driven software, ACQ.BAS written in BASIC language of the PC-ACQUISITOR, was modified for automatic rice aeration. The modified software of the automatic aeration system consisted of three main parts : a main program for data acquisition, recording on disks, and continuous monitoring ; a subroutine program for special calculations ; and a subroutine program for control/alarm. Moisture content, dry matter loss, and deterioration index of the stored rough rice were calculated in one subroutine program. A control program based on the control criteria was written in another subroutine program to operate the aeration equipment.

III. RESULTS AND DISCUSSION

3.1 Pressure Drop Model of Rough Rice

The effects of air velocity and rice moisture content on the static pressure drop of air through rough rice with 0.9% foreign material at air temperatures of 25℃ and 38℃ were analyzed. As the airflow increased, the pressure drop of air through rough rice increased (figure 3). The effect of air temperature on the resistance of rough rice to airflow was not significant at the 5% level in t-tests, though the static pressure drops at air temperature of 38℃ showed slightly higher values than those at an air temperature of 25℃ (figure 3).

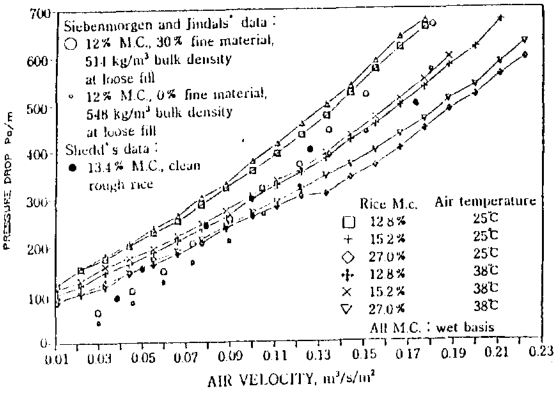


Fig 3. The effects of air velocity, rice moisture content, and air temperature on the pressure drop of air through rough rice with 0.9% foreign materials.

The effect of rice moisture on the pressure drop of air through rough rice was significant at the 5% level. Resistance of rough rice to airflow at low rice moisture content was higher than that at high rice moisture content because the void among rice kernels and the sphericity of rough rice decreased as rough rice dried. However, the effect of rice moisture on the pressure drop at low airflow rates was less than that at high airflow rates.

The effect of rice moisture content on airflow resistance was similar to that of corn as reported by Shedd (1953) and Haque et al. (1982). Shedd (1953) found that corn with 20% or more moisture had less resistance to a given airflow rate than the same corn after it had been dried, while Patterson (1963) and Matties (1956) reported that pressure drop through corn increased with an increase in moisture content.

Pressure drop values of air through rough rice were similar to Shedd's values at airflow rates of more than 0.05 $m^3/s/m^2$, but they were greater than Shedd's values at low airflow rates of less than $0.05 m^3/s/m^2$. The reason may be that the affect of air velocity on static pressure drop was higher at low airflow rate than that at high airflow rate. The effect of airflow rate on static pressure drop at high airflow rate was more significant than that at low airflow rates.

The pressure drop could be expressed as a function of airflow rate at each moisture level of rough rice. The relationship between the common logarithm of pressure drop and common logarithm of airflow rate is shown in model 1. Pressure drop at each moisture level of rough rice could be accurately predicted with the following model :

Model 1. $\log(P) = a * \log(Q) + b * \{\log(Q)\}^2 + c$, $R^2 > 0.99$

where, P = pressure drop (Pa/m),

Q = airflow rater($m^3/s/m^2$)

a, b, c = regression coefficients

a = 1.7549, standard error = 0.043

b = 0.4333, standard error = 0.018

c = 3.8069, standard error = 0.070

or $c = 3.9915 - 0.0098 * M$, $R^2 = 0.8$

M = rice moisture content, %, wet basis.

A generalized pressure drop model to predict the resistance of rough rice to airflow at various rice moistures was developed as follows :

Model 2 : Generalized pressure drop model

$$P = 43.585\ Q + 4876.595\ Q^2 - 60.965\ M * Q + 87.317,\ R^2 = 0.978$$

at $0.011 < Q < 0.220$ and $12.8 < M < 27.0$

where, P = pressure drop (Pa/m),

Q = airflow rate ($m^3/s/m^2$),

M = rice moisture content (%, w.b.).

This static pressure drop model developed by a stepwise method of regression analysis had the same independent variables as those of Haque (1982) for wheat, sorghum, and corn, The generalized pressure drop model could be used for predicting the resistance of rough rice to airflow at various rice moistures and and airflow rates.

3.2 Respiration Model of Rough Rice

A. The Effects of Rice Moisture and Air Temperature

The effects of rice moisture and air temperature on the carbon dioxide produced due to the respiration of rough rice stored at high moistures of 20%, 21%, and 22% (w.b.) are shown in figure 4. The rough rice stored at high moisture content produced much more carbon dioxide than the rice at low moisture at a fixed air temperature of 20℃ during same period. The effect due to a difference of 1% (w.b.) rice moisture on respiration rate was statistically very significant at the 1% level in t-tests. The effect of air

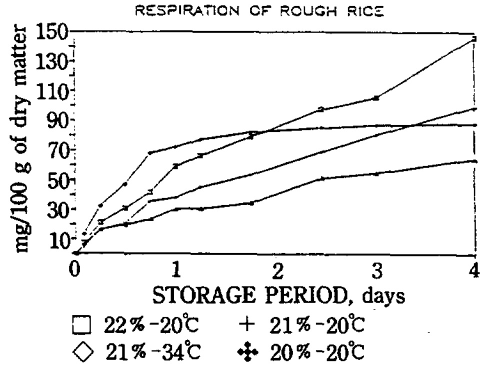


Fig 4. Carbon dioxide produced due to respiration of rough rice at high moisture content.

temperature at a fixed rice moisture of 21% (w.b.) was also highly significant, but the effect decreased after an initial increase during storage because the stored rice was being dried at high temperature of 34℃. The dry matter loss due to respiration of rough rice at the high moistures is shown in figure 5.

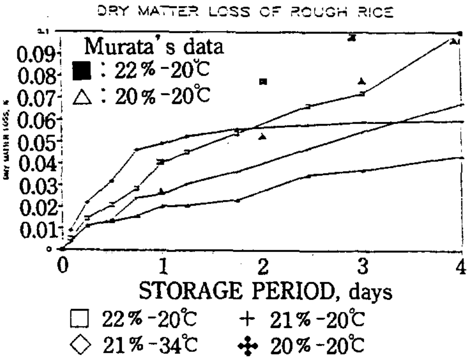


Fig 5. Dry matter loss due to respiration of rough rice at high moisture content.

The effect of air temperature on carbon dioxide produced at a low rice moisture level of 13.8% (w.b.) was investigated. Higher amount of carbon dioxide was produced with higher air temperature during rice storage. However, the effect of air temperature decreased as the storage time increased because the rice stored at high air temperature dried further to lower moisture.

The effect of rice moisture on the carbon dioxide produced due to respiration at 27℃ air temperature is shown in figure 6. The effect of rice moisture in the range of 13.8% to 22.8% (w.b.) was very significant at the 1% level, and the carbon dioxide increased with the storage period. Though the carbon dioxide increased proportionally with time initially during storage, its rate of the increase decreased slightly as the storage time increased. Figure 7 shows the effect of rice moisture on the dry matter loss of rough rice at different rice moistures and a fixed air temperature of 27℃. The dry matter loss of rough rice at 22.3% moisture reached the allowable upper limit of 0.5% in a storage period of about 11 days.

B. Respiration Model

A respiration model for rough rice was developed based on the seventy six sample data collected on the carbon dioxide produced due to the respiration of rough rice at different moistures and air temperature. The carbon dioxide was expressed as a function of rice moisture, air temperature, and storage time. The model is

$$\mathrm{Log}(CO_2) = a * MC + b * TEMP + c * \mathrm{Log}(TIME) + d, \quad R^2 = 0.963$$

$$DML = 0.682 * CO_2/1000$$

where, CO_2 : carbon dioxide, mg/100g of dry matter

MC : rice moisture content, %, w.b.

TEMP : air temperature, ℃

TIME : storage time, days,

LOG : common logarithm

$a = 0.1978$, $b = 0.0174$, $c = 0.7884$, $d = -2.8760$

DML : dry matter loss, %

In the t-tests on the parameter estimates, rice moisture was more significvant than air temperature. The regression coefficients of the model were tested by the multicollinearity test of SAS. The variance inflations of the regression coefficients were less than 1.2, and the Eigen condition numbers of the regression coefficients were less than 19 in the model. Hence, the model had very stable and consistent regression coefficients. The test of normality using the UNIVARIATE procedure of SAS also showed that the residual terms had a nearly normal distribution. The Shapiro-Wilk statistic, a criterion of normality, was greater than 0.99.

C. Comparison with Published Models

Murata et al. (1976) determined dry matter loss using a respiration model to evaluate the respiration heat as a function of moisture content and temperature. Murata's data on the dry matter loss showed higher values than those in this study in figures 5 and 7. Murata's model might overpredict the dry matter loss because his model was developed based on the respiration heat, which may be mainly produced due to the respiration of storage fungi. Also, the effect of storage time was not considered in his model. The increasing rate of the carbon dioxide produced due to respiration of rough rice decreased with storage time.

Teter's model was developed based on the carbon dioxide produced during rice storage in tropical climates without considering the effects of air temperature and storage time. The data on the dry matter loss in this study showed similar trend to Teter's data at a low moisture of 13.8% and 27℃ However, the effects of air temperature and storage time were not included in Teter's model in the limited moisture range of 10 to 17% (w.b.).

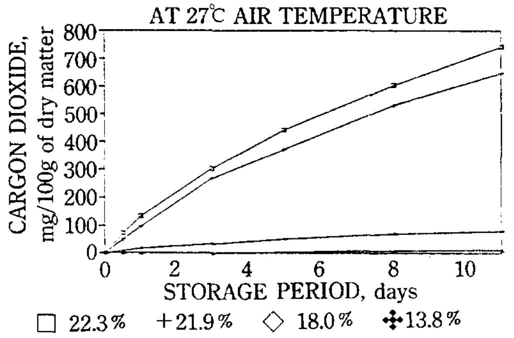


Fig 6. The effect of rice moisture on the carbon dioxide produced due to respiration of rough rice at 27℃ air temperature.

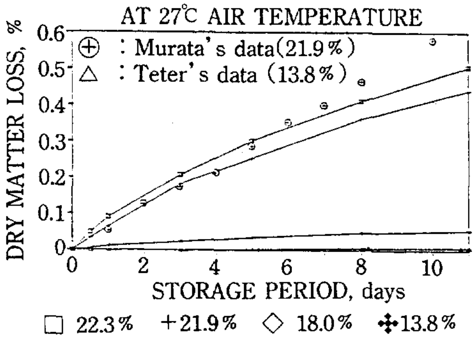


Fig 7. The effect of rice moisture on dry matter loss of rough rice at 27℃ air temperature.

3.3 PC-Based Automatic Aeration of Rough rice

A. Control Criteria for Rice Aeration

Control criteria for rice aeration were determined on the bases of data obtained from a continuous monitoring system for stored rice and of recommendations from a literature review. These are as follows :

i) Temperature

The optimum temperature recommended for rice storage is below 15℃, for the activities of insect and molds are greatly inhibited at low temperatures. It was impossible to maintain such a temperature in an in-bin rice storage system without an air conditioning unit in Louisiana except winter. The temperature and relative humidity of air in Louisiana are very high, especially humidity. The mean daily temperature in August was in the range of 23 to 34℃, and in

December it was in the range of 6 to 17℃. The rice temperature distribution in the model bin was highly affected by such ambient air. The mean rice temperature increased as mean daily ambient temperature increased. Hence, aeration for stored rice was periodically required for at least half an hour in order to slow down the activities of insects and storage-fungi and to get uniform rice temperature and moisture content. As ambient air temperature was usually greater than rice temperature during the daytime, air with low temperature and humidity was recommended for aeration. Rough rice along the periphery of the bin was heated by solar radiation during the daytime, and rice along the periphery of bottom layer was also influenced by radiation of ground. The temperature gradient due to solar radiation existed along the south to north axis. As an example, the rice temperature at wall-side of south was higher than that of rough rice located at the center by 3 to 6℃, and the temperature of bottom layer was higher than that of top layer in February. The temperature differential along the center was less than 2 to 3℃. The temperature gradients due to solar radiation did not cause non-uniform distribution of rice moisture because of insulating properties of rough rice. However, the temperature differential, which depends on solar radiation levels, may cause a little horizontal moisture migration and natural convection and provide conditions for growth of insects and molds. The natural convection due to ambient air may also cause rice spoilage by moisture accumulated at the top or the bottom of the bin. Temperature differential of more than 6℃ in the bin was estimated due to deterioration of a hot spot caused by respiration of rough rice and storage-fungi in this study. Such a hot spot was detected by a continuous monitoring system and removed by aeration or mixing.

ii) Relative Humidity

Equilibrium relative humidity (ERH) of intergranular air was one of the most important factors that affected grain quality. Moisture content of stored rough rice was mainly influenced by relative humidity of intergranulaar air. It was found that stored rice reaching near-equilibrium with a relative humidity of 75% at a temperature in the range of 15℃ to 23℃ had a moisture content of about 14% (w.b.). The mean daily relative humidity in August and December in Louisiana was about 78%, and the humidity was in the range of about 64% to 91% during a day. This weather condition was not adequate for storing rice. The intergranular air was affected by high humidity and temperature of ambient air. Hence, the ERH of intergranular air was continuously measured by electronic humidity sensors. Then, if ERH of intergranular air was more than 75% and the differential of ERH was greater than 5%, aeration was carried out with air of low airflow rate to maintain rice moisture below 14% (w.b.). The 5% difference of ERH meant difference of about 0.5% (w.b.) in rice moisture content at the same temperature.

Pym et al. (1985) recommended aeration when ERH of rough rice is greater than air relative humidity plus 5%. However, this was meaningless in a bin system because relative humidity of ambient air was usually high in Louisiana. If aeration occurred when relative humidity of ambient air was high, a zone of high-moisture rice would develop at the location where air first contacted the rice. Thus, a dehumidifier and a fan together were operated when aeration was required during a rainy season with high relative humidity of more than 90%. The operation of a fan and a dehumidifier was continued until the next measurement with a predetermined time interval. However, the cooling time of aeration should be determined according to airflow rate, amount of stored rice, rice and environmental conditions, etc.

iii) Moisture Content

Moisture content is the most critical factor in the rate of deterioration of stored rice. Aeration is recommended according to U.S. Standards for Rough Rice (1968) when rice moisture is more than 14% (w.b.).

If rice moisture exceeded 16%, the operation of a heater and stirrer were required together with the fan. Rice moisture could be determined by near quasi-static equilibrium moisture content (Near EMC) models of rough rice developed in another study (Chung, 1989). Chung-Pfost's static EMC model (CP), overpredicted the moisture content of stored rough rice, while the near quasi-static EMC models of Modified Chung-Pfost's model (MCP) and Remodified Henderson's model (RMH) predicted well the moisture content of rough rice stored in a model bin in winter with R^2 of 0.94. However, the MCP's model (Chung, 1989) predicted more accurately and consistently than the RMH's model based on actual data of rice moisture. In addition, when a high moisture gradient of rice of a hot spot in a storage-bin was detected, the operation of a fan with a stirrer was recommended.

iv) Dry Matter Loss

The developed respiration model of rough rice could be used to determine dry matter loss of stored rough rice. Aeration is recommended when dry matter loss exceeds 0.5% (USDA, 1968). However, this criterion was not necessary in this automatic aeration system of rough rice because dry matter loss of rice under such a control system could be maintained below 0.5 %.

v) Deterioration Index

The suitability of air for aeration can be assessed by analyzing a deterioration index (DI) of air. Teter (1981) and Pym et al. (1985) recommended aeration when the deterioration index of air is less than 5. However, in this study DI of grain in the bin was determined with temperature and relative humidity of intergranular air and was used as a control criterion. These DI values can represent exact conditions of rice. The critical value of DI of rice was determined by 4.5 as a control criterion for aeration in a bin system because rice moisture contents were found to be about 14% (w.b.) when DI of rice in the bin was less than 4.5. The critical DI of air for aeration should be also 4.5. Change in the deterioration index of rice was very similar to that of the rice moisture.

The only control for temperature and relative humidity of aeration air was enough to maintain DI below 4.5. Hence, a control based on DI was not necessary in th model bin system.

B. Automatic Aeration of Rough Rice

A PC-based automatic aeration system of rough rice, which was based on the control criteria, was developed to maintain rice quality. Flowcharts in figure 8a and 8b show control logic for automatic aeration of rough rice. In the automatic in-bin rice aeration, there still existed a temperature gradient of rice in the bin due to solar radiation during the daytime.

However, the gradient of rice temperature was less than 5 to 6℃, which was a result of automatic aeration based on the control criteria. Temperatures of intergranular air showed a trend similar to the rice temperatures.

As an example of automatic rice aeration, the conditions of stored rice were illustrated in figures 9, 10 and 11. Changes in relative humidities of intergranular air at certain locations and in ambient air under automatic control are shown in figure 9. The Relative humidity of intergranular air was kept less than 75% except

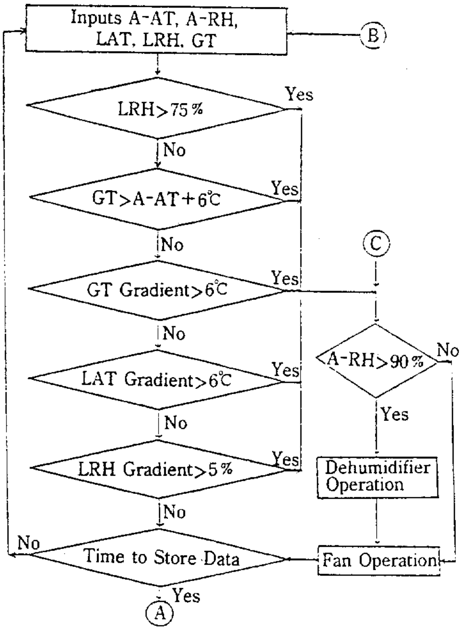
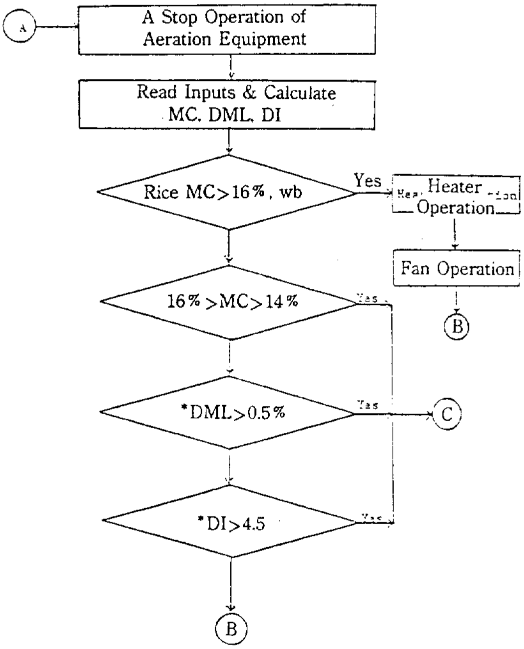


Fig 8a Flowchart of the control subprogram for automatic aeration of rough rice.



Note :
- A-AT, A-RH : ambient air temperature and relative humidity
- LAT, LRH : temperature and rel. humidity of intergranular air
- DML : dry matter loss, DI : deterioration index.
- * : not necessary as control criteria.

Fig 8b Flowchart of the control subprogram for automatic aeration of rough rice.

in the beginning of the aeration because relative humidity of 75% was used as one of the control criteria. Rice moistures predicted by the Remodified Henderson's model and the Modified Chung-Pfost's model under automatic control of aeration were consistently less than 14% except in the beginning, figure 10. Deterioration indices of the rough rice stored under automatic control decreased from initial values of 4.5 and 5.2 to values below 4.5 as shown in figure 11, while the DI of rough rice stored under no aeration control fluctuated between 3.5 and 7.0 in

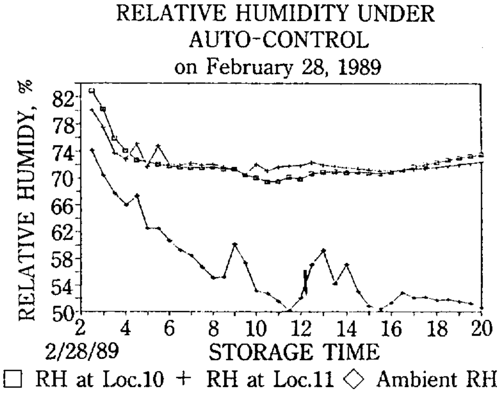


Fig 9. The change of air relative humidity under automatic control of aeration.

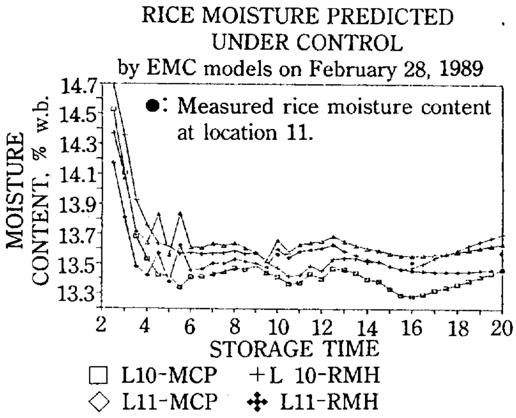


Fig 10. Rice moisture predicted by re-modified Henderson's model and modified Chung-Pfost's model under automatic control of aeration.

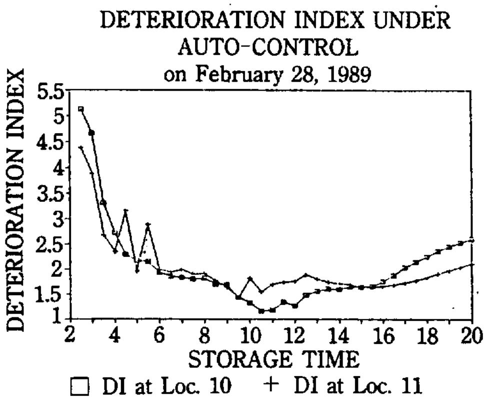


Fig 11. The change of deterioration index of air under automatic control of aeration.

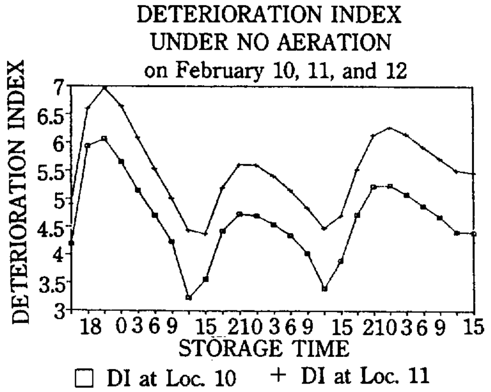


Fig 12. The change of deterioration index of air under no aeration.

figure 12. Changes in DI under automatic control corresponded to rice moisture contents under automatic control (figure 10). It is clear that the aeration system developed here based on control logic, maintained rice quality by controlling the aeration equipment automatically.

Ⅳ. CONCLUSIONS

1. A more accurate pressure drop model for use in rough rice aeration was developed. The effect of rice moisture on airflow resistance of rough rice was significant at the 5% level. Dried rough rice showed higher resistance to airflow than wet rough rice at same grain depth.

2. A static pressure drop model for each moisture level of rough rice is as follows :

$$\log(P)=a*\log(Q)+b*\{\log(Q)\}^2+c,\quad R^2=0.99$$

where,P : static pressure drop (Pascal/m)

Q : airflow rate ($m^3/s/m^2$)

a : 1.755, b=0.433, and c=3.991−0.0098 *M

M : rice moisture content, % (w.b.).

3. A generalized model to predict static pressure drop of air through rough rice is as follows :

$$P=2843.59Q+4876.60Q^2-60.97M*Q+87.32,\quad R^2=0.978$$

4. A respiration model was developed to determine dry matter loss of rough rice as follows :

$$\mathrm{Log}(CO_2)=a*MC+b*TEMP+c*\mathrm{Log}(TIME)+b$$

where, CO_2 : carbon dioxide, mg per 100gram of dry matter

MC : rice moisture content, % (w.b.)

TEMP : air temperature, ℃

TIME : storage time, days

a=0.1978, b=0.0174, c=0.7884, d=−2.8760

5. Control criteria on moisture content, equilibrium relative humidity, grain temperature, and deterioration index were determined and recommended for automatic aeration system.

6. The PC-based automatic aeration system based on the aeration criteria controlled stored rough rice well and maintained it at a moisture content below 14% (w.b.), DI below 4, and without any damage from storage molds.

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