強制通風降低貯穀溫度之效果

Forced Aeration of Rice in Warehouse

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摘要

本文探討强制式通風作業降低貯穀溫度之效果，並應用複廻歸分析法探討影響穀物通風之因素。

Summary

Aeration experiments were carried out in a concrete warehouse with a storage volume of 29 x 11.6 x 6 cubic meters, loaded with 1123 tons of rough rice. The analysis is based on the storage phenonmenon during summer aeration under subtropical weather in Taiwan. Stepwise regression was used for multiple linear regression analysis of the controlling factors on aeration.

INTRODUCTION

In Taiwan, the harvest season of the first rice crop lasts from May through July, and that of the second crop begins in September and ends in November. The annual rice production in Taiwan is about 2,500,000 metric tons. Most of the paddy is stored as bulk or in bags in flat reinforced-concrete warehouses operated by local farmer's associations. Only small portions of paddy are stored in silos. Every year, more than 500,000 tons of paddy are stored, and the storage periods range from 6 to 18 months. The storage loss ranges from 0.165% to 2.406%, depending on the kind of storage warehouse. The milling yield of the stored paddy is around 77% (Lu et al., 1979). Average seasonal ambient air temperature in Taiwan is 15-30°C, and humidity is 75-90%.

Factors influencing grain quality and quantity in storage include temperature, moisture, grain properties, molds, microorganisms, insects, rodents, and birds.

Normally quality of paddy rice does not deteriorate much during the first six months in storage, but quality may deteriorate significantly after six months if a favorable storage environment cannot be maintained. Schroeder and Halick (1963) pointed out that deterioration proceeds at an accelerated rate as time in storage, relative humidity, and the initial moisture content of the rice increases.

During storage, the grain interacts with its environment, exchanging heat and moisture. Temperature and moisture content are variables that have been given considerable emphasis in the study of detrioration of grain in storage.

Loss of quality is accelerated more by high moisture content than by high storage temperature. Therefore, paddy rice should be dried to a safe moisture content before being put into the storage bin. If dried rough rice is to be stored for a few months or longer, the storage bin should be supplied with natural ventilation or forced aeration in order to convey the heat generated by respiration or weather out of the storage bin.

The amount of control of grain temperature, whether it is done by ventilation or forced aeration, depends on ambient air conditions. When the ambient air is cooler than the stored grain, low-volume aeration can be used quite efficiently to cool the grain: fans are used to convey small volumes of ambient air upward or downward through the stored grain in such a way that the grain temperature is reduced to a level for safe storage.

Aeration cannot only lower stored grain temperature but also equalize grain temperature through the bulk and reduce the thermal gradient caused by seasonal ambient temperature variations. It can also remove unpleasant odors or toxic gases after fumigation. Air-flow rate adopted in cooling the stored grain is between 0.052 and 0.15 m^3/min per ton grain (Foster and Tuite, 1982; Mclean, 1980). Calderwood et al. (1984) reported that rough rice was stored successfully long-term (up to 54 months) with the help of aeration and control of stored-grain insects in a bin with a storage capacity of 9.52 tons.

There is resistance to air flow inside bulk grain when air is forced to pass through the bed of grain. The amount of resistance offered by the grain to air flow is a function of grain size, shape, amount, packing, bed depth and air velocity (Brooker et al., 1974).

A factorial experiment containing such factors as paddy variety, packed bed porosity, air superficial velocity, and air conditions was carried out by Bowrey and Intong (1983). They reported that effect of the changes in temperature and relative humidity of the ventilating air on the pressure drop was not significant, but both porosity and superficial velocity affected the pressure drop significantly. The difference in pressure drop caused by variety was also very significant even in conditions with the same porosity and velocity.

The objective of this paper is to investigate the effect of forced aeration on the cooling of paddy rice stored in a commercial warehouse located in a subtropical area.

MATERIALS AND METHODS

Field aeration experiments were carried out in a flat concrete warehouse located in Shin-fong Farmer's Association in northern Taiwan. The warehouse has a storage volume measuring 29 x 11.6 x 6

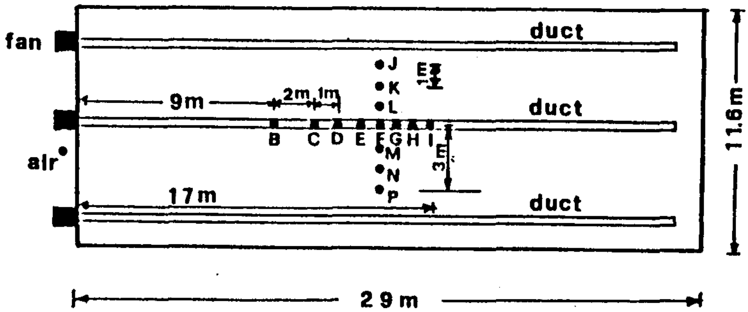

Fig. 1. Aeration ducts and locations for measuring temperature.

meters and is equipped with three centrifugal fans of 7.5 hp to blow the air upward through the bulk paddy. The airflow rate of each fan is 80 m^3/m, and static pressure of each fan is 70 mm H_2O. The aeration system consists of three perforated rectangular ducts installed under the warehouse floor. Each duct is 27 meters long with a cross-section measuring 0.5 x 0.5 m. The warehouse was loaded with 1123 tons of short-grain paddy rice of the first crop of 1981 on August 16, 1981. The aeration rate for the stored paddy was 0.2 m^3/min per ton paddy.

The temperature-measuring system was set up on April 3, 1982. The temperature was measured by inserting T-type thermocouple cables into bulk paddy and recording the data on a KAYE DIGISTRIP II data logger. The measuring points where temperature sensors were inserted were at 1 meter (upper layer), 2.5 meters (middle layer), 4 meters (lower layer), and 5.5 meters (bottom layer) below the bulk paddy surface. The depth of the stored grain was 6 meters. Sensors were inserted at all four measuring points near the center of the warehouse at location F (Fig. 1). At other locations, only one sensor was inserted at each point. The depth locations of the sensors at these points are as follows: 4 m at points B, E, G, L, and M; 2.5 m at D, H, K, and N; and 1 m at C, I, J, and P. Locations B, C, D, E, F, G, H, and I were distributed along a central duct.

A statistical analysis based on Tsay's data (Tsay, 1987), obtained from laboratory simulation study on the temperature transition of paddy rice in bulk storage under forced aeration, was also analyzed. The air temperature and humidity were simulated by controlling an environmental test chamber. A small-scale circular bin 30 cm in diameter and 72 cm in height, loaded with 40 kg rough rice of 13% moisture content was placed in the environmental test chamber for an aeration study. The control air was blown upward through the bin. The experimental treatments were chosen by the combination of four controlling variables to simulate actual aeration conditions in Taiwan. The test ranges for those variables were air-flow rate from 0.25 to 1.66 m^3/min per ton paddy, air temperature from 20 to 32°C, air humidity from 60 to 90%; and initial paddy temperature from 35 to 40°C.

RESULTS AND DISCUSSIONS

The 1123 tons of paddy were loaded in the warehouse on August 16, 1981. After 26 months long-term storage, the stored paddy was unloaded on October 1983 for milling; the result was 883 tons of brown rice with a milling yield of 78.62%. No deterioration was observed. The paddy moisture contents were 9.57%

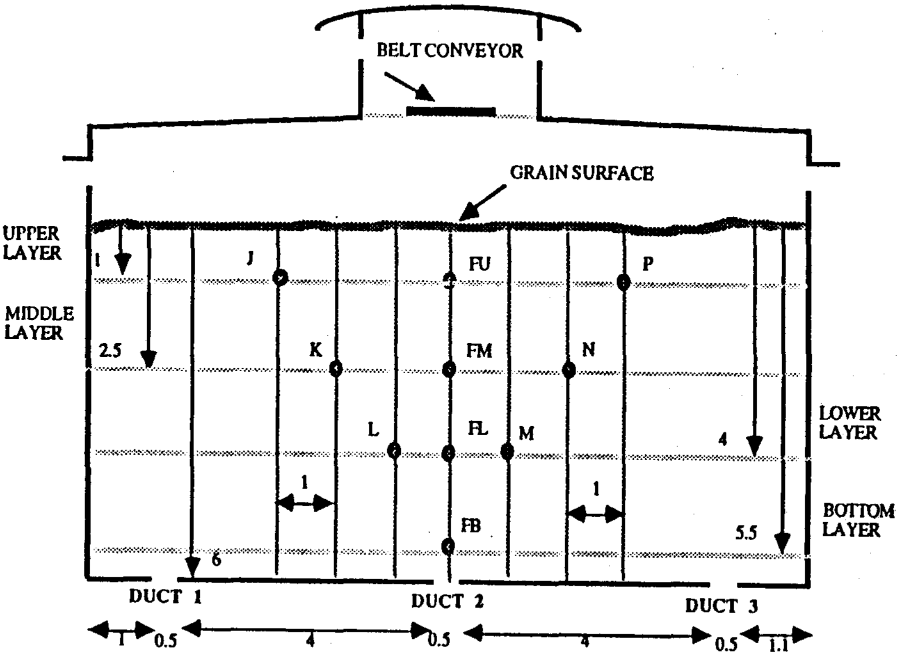

Fig. 2. Different layers and locations for inserting temperature sensors inside the bin (unit: meter)

on April 2, 1982, 9.21% on February 7, 1983, and 10.6% on October 1983. Low moisture content is one of the key factors in preventing stored grain from deteriorating during long-term storage.

Overnight aeration in summer was conducted intermittently from August 3 through August 7, 1982. The three fans were turned on in the evening around 5 p.m. and turned off the next morning around 7:30-8:30 a.m. The aeration period in each day ranged from 14.5 to 15 hours. After the first day's 14.5 hours aeration (which began at 17:02 August 3, 1982, and ended at 7:30 August 4, 1982), the temperature dropped 7.4°C (from 39.2°C to 31.8°C) for the bottom layer, 4.6°C (from 39.8°C to 35.2°C) for the lower layer, and 0.5°C (from 38.5°C to 38°C) for the middle layer, and it rose 2.1°C (from 38.6°C to 41.2°C then dropped to 40.7°C) for the upper layer of bulk grain at location F (Fig. 3). The average hourly temperature changing rates for each layer were: bottom layer −0.51°C/hr, lower layer −0.31°C/hr, middle layer −0.03°C/hr, and upper layer +0.14°C/hr.

The temperature increment in the upper layer of the bulk paddy indicated that the cooling zone did not pass through the upper layer after the first day's 14.5 hours of aeration. During the first day's aeration period, the ambient air was 27-29°C and relative humidity was 80-93%. After the fans were shut off, the paddy temperature remained fairly constant until the beginning of the next aeration (Fig. 3).

The average temperature at location F during the second day's 15-hour aeration period dropped 0.006°C/hr for the bottom, 0.06°C/hr for the lower, 0.15°C/hr for the middle, and 0.20°C/hr for the

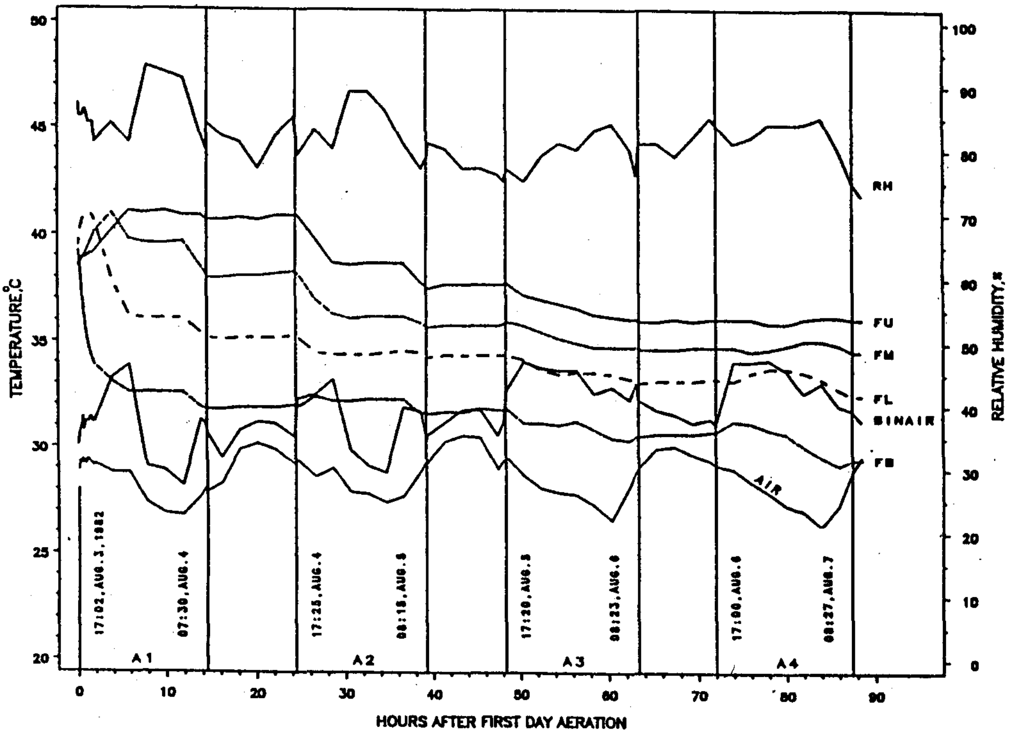

Fig. 3 Temperature variations during aeration in summer.

A1, A2, A3 and A4: aeration periods
Fu = upper layer at location F; FM = middle layer at location F; FL = lower layer at location F; FB = bottom layer at loation F; BIN AIR = air temperature measured at 0.1 m above the top paddy layer; AIR = ambient air; and RH = relative humidity.

upper layer of the bulk paddy. As the cooling zone passed through the upper layer of the bulk paddy, its temperature dropped. No significant drop in temperature resulted from the third day's aeration (Fig. 3).

Figure 4 shows three-dimensional diagrams of static air pressure variations at different locations and layers of bulk paddy around central duct 2 of figure 2.

Figures 5-7 show three-dimensional diagrams of paddy temperature variations at different locations and layers of bulk paddy before, during, and after aeration. After aeration, the paddy temperatures were characterized by a high temperature in the top layer and a low temperature in the lower and bottom layer of the bulk grain. Temperatures were lower for those points right on top of the central aeration duct than for those away from the duct. This result matched well with the pressure distribution inside the bulk grain around central duct.

In the statistical analysis of the laboratory aeration-simulation study, the cooling rate for each combination of treatments was calculated by dividing the difference in temperature between the middle layer of the bulk paddy column and inlet air before aeration by half cooling time. The half cooling time is defined as the time required to reduce this temperature difference by one-half

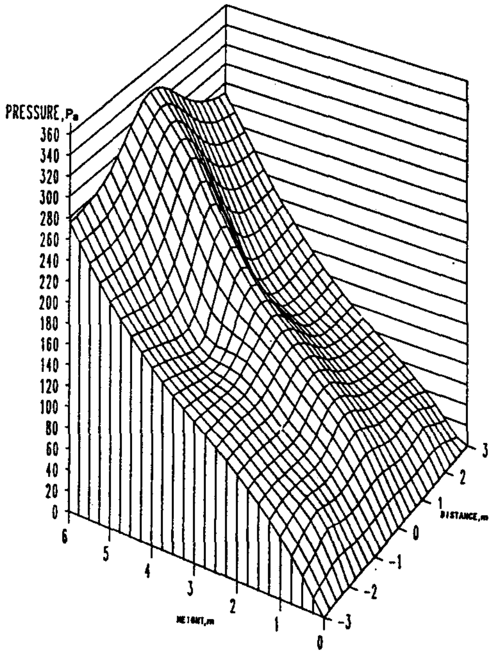

Fig. 4. Air pressure around central duct at location F.

DISTANCE = distance against location F, measured perpendicular to central duct, m; HEIGHT = height against floor, m; and PRESSURE = air pressure, pascal.

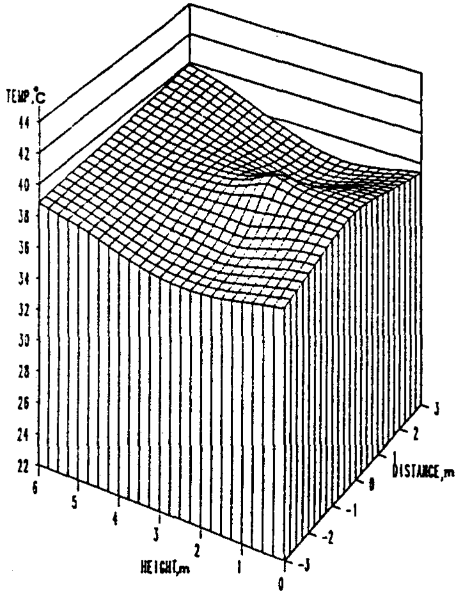

Fig. 5. Temperature distribution before aeration on August 3, 1982.

DISTANCE = distance against location F, measured perpendicular to central duct, m; HEIGHT = height against floor, m; and TEMP = paddy temprature, °C.

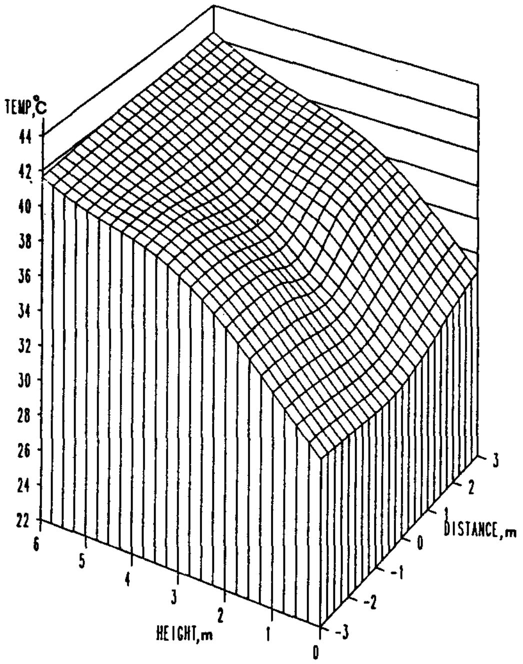

Fig. 6. Temperature distribution after 14.5 hours aeration on August 3, 1982.

DISTANCE = distance against location F, measured perpendicular to central duct, m; HEIGHT = height against floor, m; TEMP = paddy temperature, °C.

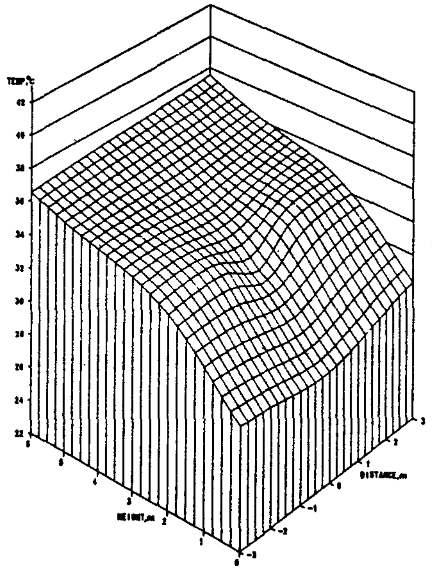

Fig. 7. Temperature distribution after aeration on August 7, 1982.

DISTANCE = distance against location F, measured perpendicular to central duct, m; HEIGHT = height against floor, m; TEMP = paddy temperature, °C.

Table 1. Rice cooling rates and controlling variables in aeration test.

Case	Cooling Rate °C/hr Y	Initial Rice Temperature °C X1	Air Temperature °C X2	Air Humidity % X3	Aeration Rate CMM/tom X4	Temperature Difference °C X5=X1−X2
1	2.19	35.0	20.1	76.2	1.66	14.9
2	.43	35.1	32.0	88.0	1.66	3.1
3	.73	35.1	26.0	88.0	.99	9.0
4	.15	35.0	31.9	88.4	.25	3.1
5	.15	35.5	32.0	76.4	.25	3.5
6	1.38	35.3	25.9	67.5	1.66	9.4
7	.14	35.3	31.9	64.3	.25	3.4
8	.48	35.1	20.1	89.4	.25	15.0
9	1.24	35.2	26.0	87.6	1.66	9.2
10	1.72	36.0	19.8	76.5	.99	16.2
11	.44	35.1	31.8	76.8	.99	3.3
12	1.62	35.0	26.1	72.7	1.66	8.9
13	.41	35.1	26.1	83.6	2.5	9.0
14	.82	35.4	19.8	65.1	.25	15.6
15	.24	35.7	32.3	84.9	.99	3.4
16	1.01	35.2	20.1	74.8	.25	15.1
17	1.33	35.1	20.2	84.4	.99	14.9
18	.56	34.9	26.0	74.9	.25	8.9
19	.58	35.1	32.1	75.1	1.66	3.0
20	1.57	35.3	25.9	66.2	.99	9.4
21	2.38	35.1	19.6	61.0	1.66	15.5
22	.87	39.8	19.9	88.2	.25	19.9
23	.84	39.8	20.0	75.3	.25	19.7
24	.94	39.9	31.9	66.0	.99	8.0
25	1.89	40.0	20.0	92.0	.99	20.0
26	1.37	40.2	32.0	88.7	1.66	8.2
27	.44	40.2	31.8	65.3	.25	8.4
28	1.28	40.0	25.9	76.3	.99	14.1
29	1.03	40.0	31.7	79.1	.99	8.9
30	1.04	40.2	25.0	76.9	.25	14.2
31	2.38	40.2	25.8	79.1	1.66	14.3
32	.99	40.3	31.9	83.7	.99	8.4
33	.69	39.9	26.1	85.6	.25	13.8

during aeration.

Stepwise regression (P2R of BMDP statistical package) was used for multiple linear regression analysis of the data set in table 1. All possible subsets regression (P9R) was also adopted as a guide to find "best" subsets of predicator variables. Since there were only two levels in variable X1 (subgroup 1 - low initial rice temperature of 35±1°C, and subgroup 2 =

Table 2. Results of regression analysis.

	Case	Step	Variables Selected	Regression Coefficient	Standardized Regression Coeff.	Y Intercept	Cp Value Corresponding To The Selected Variables	R^2	F	Residual SS
Subgroup 1 (35°C)	21	3	X2	–0.0869	–0.644	4.0470	23.72	0.8949	48.26**	0.9727
			X3	–0.0189	–0.248			(if delete X2 and include X5 R^2 = 0.8940)		(if delete X2 and include X5 SS = 0.9772)
			X4	0.6488	0.580					
Subgroup 2 (40°C)	12	2	X4	0.9476	0.957	–0.4615	7.54	0.8529	27.47**	0.4380
			X5	0.0658	0.587			(if include X3 R^2 = 0.8670)		(if include X3 SS = 0.4141)
Population (35 & 40°C)	22	3	X3	–0.0141	–0.195	0.5497	2.30	0.8564	57.65**	1.8266
			X4	0.7711	0.709					
			X5	0.0829	0.691					

X2 = air temperature; X3 = air humidity; X4 = airflow rate; X5 = temperature difference, and ** = significant at 0.01 probability level.

high initial paddy temperature of 40±1°C), the comparison of regression planes was analyzed. The outputs from stepwise and subsets regression methods were summarized in Table 2 for subgroup 1, subgroup 2, and population that contained both low and high initial paddy temperature.

From the results of stepwise regression procedure, variables X2, X3, and X4 were selected in subgroup 1. Only two variables (X4 and X5) were selected in subgroup 2. Three variables (X3, X4, and X5) were selected in the population either by stepwise or subsets regression method. Variable X1 (initial paddy temperature) were removed from the regression planes in subgroup 1, subgroup 2, and population. If X3 was forced into the regression plane of subgroup 2 together with the already selected variables X4 and X5, it showed that there was not much change in coefficient of determination R^2 (from 0.8529 to 0.8670). If X5 instead of X2 variable was included in the regression plane of subgroup 1, no change in R^2 was observed.

The F value calculated from the method of analysis of comparing regression planes (Afifi and Clark, 1984) was 1.83. Since F test was non-significant at 0.05 probability, only one regression plane was required to explain the result of the simulation study. The regression plane derived from the pouplation was listed below with $R^2 = 0.8564$.

$$Y = 0.5497 - 0.0141\ X3 + 0.7711\ X4 + 0.0829\ X5$$

The residual plots showed that no systematic deviation from the fitted response plane was present, and that the error variance varies either with the level of Y or with the levels of X3, X4, or X5. The standardized regression coefficients were –0.195, 0.709, and 0.691, respectively, for X3, X4, and X5. Therefore, variables X4 (airflow rate) and X5 (temperature difference) have a positive effect on paddy cooling, and their influence on cooling are about triple as important as the negative effect variable X3 (air humidity). Thus, the airflow rate and initial temperature difference between stored paddy and ambient air before aeration are the dominant factors on paddy cooling during aeration.

CONCLUSIONS

During long-term storage, the grain located at upper and middle layers of the bulk grain maintain a higher temprature year-round than the lower and bottom layers. In summer, it took two overnight aeration processes to move the cooling zone through the upper layer of bulk paddy.

Temperatures were lower for those points right on top of the central aeration duct than those away from the duct. This result matched well with the pressure distribution inside the bulk grian.

Small-scale simulation study of paddy aeration showed that the aeration rate and initial temperature difference between stored paddy and ambient air before aeration are the dominant factors controlling the cooling rate during aeration of bulk paddy.

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