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Changes in RH and wet-bulb temperature of an Indica paddy bulk in a large warehouse in southeast China

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Abstract

Based on the isotherm of indica paddy, the relative humidity and wet-bulb temperature in the intergranular air of a paddy bulk were calculated using the Newton-Raphson method. The dry-bulb temperature, relative humidity, and wet-bulb temperature in 3500 tonnes of the paddy bulk were measured. Fumigation was conducted from 29 April to 28 June, 2019 and air-conditioned cooling was carried on from 17 July to 15 October, which kept Layer 1 of the paddy bulk below 26°C. The average dry-bulb temperature in Layers 2, 3 and 4 from August to September was below 24.5°C, 22.5°C and 22.5°C, respectively. The relative humidity in Layers 1, 2, 3 and 4 was below 58%, which indicated that the paddy was dry. The wet-bulb temperatures in Layers 1, 2, 3, and 4 were below 20°C, 18.5°C, 17°C, and 17°C, respectively, which suggested a possible insect infestation in Layer 1 and 2. In 2020, the nitrogen treatment was conducted from 23 March to 25 September, and a cooling from 11 May to 25 June kept Layer 1 of the paddy bulk below 25°C. The average dry-bulb temperature in Layers 2 and 3 from August to September was below 23°C. The relative humidity in Layers 1, 2, and 3 was below 60%. The wet-bulb temperatures in Layers 1, 2, and 3 were below 20°C, 18°C, and 17°C, respectively. The fees for fumigation and cooling in 2019 were 3.05 RMB per tonne of paddy. In 2020, the fees for fumigation and nitrogen treatment were 6.31RMB per tonne.

Keywords: Indica paddy, Storage cost, Air-condition, Fumigation, Nitrogen treatment, Wet-bulb temperature, Relative humidity

Introduction

Rice is amongst the oldest domesticated cereal grains in the world, and it is estimated that ten billion people will consume rice as main food and that the demand will be around 880 million tonnes by the year of 2025 (Rehal et al., 2017). The total rice production was 472.3 million tonnes with China leading in rice production of 144 million tonnes and India following with a production of 106 million tonnes in 2014 (FAO, 2014). Rice is a difficult to handle cereal in that head rice and grain breakage can seriously affect market value (Iguaz and Vírseda, 2007). The evaluation parameters for the efficiency of paddy processes are head rice percentage and whiteness (Yadav and Jindal, 2007), and the moisture content (m.c.) of paddy is an important factor for these two parameters. A test in vertical mill suggested the optimal m.c. for paddy processing is 15% wet basis (Yan et al., 2005). But in practice, the long-term safe storage m.c. of indica paddy is usually lower than 13.5%. In south China, the main storage technology for dry paddy is to control the damage caused by pests. Thus, air-conditioners and nitrogen-filling techniques are being extensively applied. Few studies deal with the intergranular air properties in a large grain bulk. Changle Depot of Fujian Provincial Grain Reserve Administration Co. Ltd. is located at the Fuzhou Plain, China. This region belongs to a climate of subtropical marine monsoon. The present study analyzed the changes in dry-bulb temperature, relative humidity (RH), wet-bulb temperature in different layers of a paddy bulk in a large warehouse during the first-year storage with fumigation and cooling, and the second-year storage with cooling and nitrogen treatment. The overall aim was to find the variation trends of the above parameters in a paddy bulk under subtropical marine monsoon climate.

Materials and methods

Condition and management of the paddy warehouse

The experiment was carried out at the Changle Depot, Fujian Provincial Grain Reserve Administration Co. Ltd.. Fuzhou, Fujian province, China. This depot is located at the plain with 25.9°N, 119.5°E, and 63 meters of average altitude, which has a tropical monsoon climate. The average annual temperature in this plain is 19.3°C, and average temperature in January and July is 10.3 and 28.3°C, respectively. The warehouse used in this study had an inner dimension of 42 m length and 24 m width, and was in the east-west direction. The warehouse had three pairs of U-shaped ground cage air channels along the width direction and three ground vents in the bottom of the north gable wall. Two pairs of 0.55 kW axial fans (0.55 kW power, YBF280M1-4, Huasheng Machinery Co., Ltd., Leqing City, China) were installed in two windows located at the top of north and east gables. Each fan supplied air to1.5 pairs of U-shaped air channels. The ratio of longest to shortest pathway of the supplied air was 1.35.

The late maturation indica paddy, 3500 tonnes harvested at Nanping, China was loaded into the warehouse on 24 March 2019, with a 6.1 m of grain height. The grain had 11.4% m.c.,15 mg KOH/100 g free fatty acid content, and 0.5% foreign materials. After levelling the grain bulk surface, aeration was conducted by running the four axial fans from 24 to 25 March, 2019. Three centrifugal fans (7.5 kW, Type 4-72-6C, Huasheng Machinery Co., Ltd., Leqing City, China), which provided 16576 m^3/h and1116 mmHg (148.8 kPa) static pressure, were continually run for 48 h (9:00, 31 December 2019 to the next day). The supplied air entered warehouse through the three vents and then passed upward through the grain bulk, finally was exhausted by the two axial fans. The axial fans provided a negative pressure. On 13, 15, 20, and 22 January, and 17 and 21 February, the axial fans were continually run for 16 h (from 17:00 to 11:00 on next day).

During the aeration, the warehouse doors were closed, the three vents were opened, and air duct to the four axial fans was opened. The four fans provided 320 to 220 Pa of static pressure and 9090 m^3 air per hour. Thus, the ventilation rate was 10.4 $m^3h^{-1}t^{-1}$.

Before conducting the fumigation, the bulk surface was covered with plastic films. On 29 April, 36.7 kg aluminum phosphide tablets (56%effective content, Jining Yongfeng Chemical Plant, Shandong province, China) were loaded into a phosphine generator located outside the warehouse, and the generator (LM-KF3608-VI controllable phosphine generator, Beijing Liangmao Science and Technology Co. Ltd., China) produced 350 mL/m^3phosphine. The whole warehouse was fumigated with a circulating current system till 18 June. On 19 to 27 June, the phosphine generator was stopped, but the fans were continually run to remove the phosphine from the warehouse, until no residue was detected (on 28 June).

Two air conditioners (TS-LS051S, Henan Grain Storage Equipment Technology Co., Ltd., China) were used to control the headspace temperature during summer months. The two air conditioners, which had a cooling capacity of 5880 kW, were installed on the eastern and western walls of the warehouse and located at 1.8 m above the paddy bulk surface. The supplied cooling air was evenly distributed within the suspended ceiling through eight outlets from the air conditioners. In 2019, the air-conditioners were set at 24°C, and run from 17 July to 15 October. In 2020, the air-conditioners were set at 23°C, and run from 11 May to 27 October. Nitrogen with 83.7% to 97.8% concentration was applied to the warehouse on 23 March, 6 and 13 April, 15 and 18 May, 22 June, and 15 and 24 July. The nitrogen application time at each day was 24 or 26 h. The nitrogen concentration was monitored at six locations inside the paddy bulk. The nitrogen analyzer included an air compressor (type GA75, Wuxi Atlas Copco Compressor Co. Ltd., Wuxi, China), two filters (type CTA-030), one oil remover (type CY-15), one freeze dryer (type WCD-150GF, 17 Nm^3/min capacity, Cold medium R22, Guangzhou Weiton Industry Gas Co. LTD., Guangzhou, China), and a nitrogen generator (type NP995-310B, Guangzhou Weiton Industry Gas Co. Ltd.). The nitrogen generator had a capacity of 310 Nm^3/h with 99.5% of nitrogen purity at 0.75-0.8 MPa.

Measured parameters

Grain temperature

A temperature and RH sensor located at1.5 m above the bulk surface measured the headspace temperature and RH (Fig.1). The grain bulk temperature was detected every three to four days, and 240 data of temperature were recorded in the software of Grain Status Monitoring System. Twelve cables along the width direction about 3.7 m apart were parallelly connected to a trunk which was 41 m long along the length direction. Each branch cable had five lines and was about 5.8 m apart along the width direction. Four temperature sensors were located in each line, and had distance of 0.2, 2.1, 4.0, and 5.8 m in proper order from the bulk surface, assigned as layer 1, layer 2, layer 3 and layer 4, respectively. The data for paddy bulk temperature, bin headspace RH and temperature, and ambient air RH and temperature were collected from 6 March 2019 to 27 October, 2020.

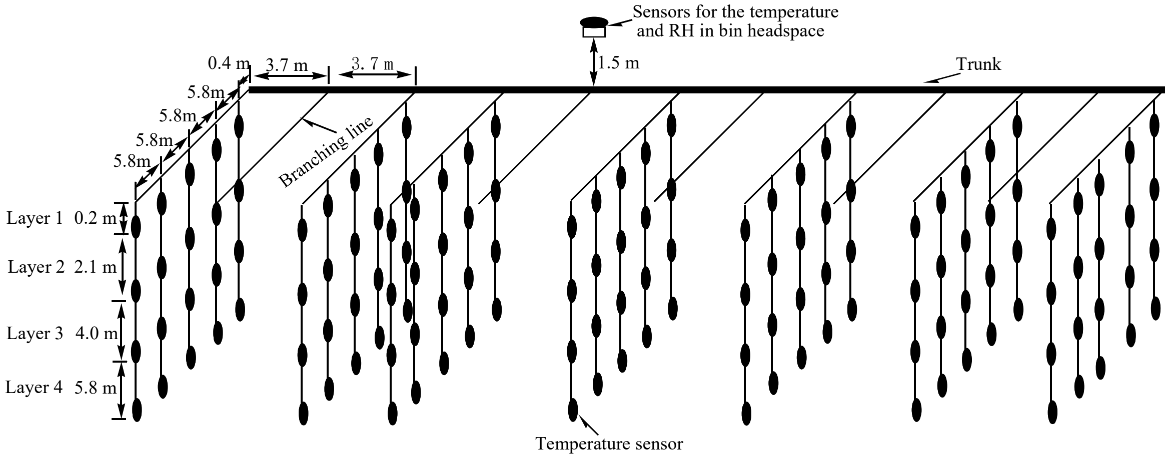

Fig. 1. Distribution of temperature sensors in the paddy bulk and a RH/Temperature sensor in the warehouse headspace.

Grain moisture content

The warehouse P27# was in west-east orientation, and had four sampling locations in the bulk surface which was about 13.7 meters apart along the north or south wall and had 0.5 m distance from the wall. Three sampling locations passed through the centre line with a location in the central point, and two other locations had 10 meters distance from the centre site. The depths of sampling were 0.3, 3.0, and 5.8 m from the bulk surface, assigned as layer L1, L2 and L3, respectively. The sampling dates in 2019 were 1March, 1 April, 2 October, and 1 November. The sampling dates in 2020 were 17 January, 18 March, and 26 October. About 0.5 kg grain was sampled at each of thirty-three locations at each sampling time. The sampled grain was kept in plastic bags (20 cm length, 14 cm width) and transferred to lab. Grain moisture content of the sample was measured using a capacitance moisture meter (LDS-1G, Taizhou Grain Instrument Factory, Taizhou, China).

Intergranular air relative humidity in grain sample

The modified Chung-Pfost equation was used to calculate the RH inside the sample:

$$RH = 100 \exp\left[-\frac{a}{T+b}\exp(-c \cdot M)\right] \quad (1)$$

Where; RH is the intergranular air relative humidity (%); M is the grain moisture content (%, wet basis); T is grain temperature(°C); and the values of a, b, c are 564.019, 63.041, and 0.219, respectively (Li et al., 2014).

The following equations were used to calculate the humidity ratio of the paddy bulk:

$$w = 0.622 \cdot \frac{RH \cdot p_s}{p_{atm} - RH \cdot p_s} \quad (2)$$

$$p_s = \frac{6 \times 10^{25}}{(T + 273.15)^5} \exp\left(-\frac{6800}{T + 273.15}\right) \quad (3)$$

Where; w is the intergranular humidity ratio of grain bulk (kg of water/kg of dry air); p_{atm} is the atmosphere pressure (101,325 Pa); and p_s is the saturation vapor pressure of intergranular air at grain temperature (Pa).

The wet-bulb temperature (T_w) was calculated as:

$$f(T_w) = w - w_w(T_w) + [4.042 \times 10^{-4} + 5.816 \times 10^{-7} w_w(T_w)](T - T_w) \quad (4)$$

Where;T_w is intergranular air wet-bulb temperature (°C); w_w is the humidity ratio of the saturation vapor pressure at the wet-bulb temperature (kg/kg).

The right-hand side of the Eq. (4) depends only on the wet-bulb temperature when $f(T_w) = 0$.

The Newton-Raphson method was used to search for the T_w (Thorpe, 2002):

$$T_w^{p+1} = T_w^p - \frac{f(T_w^p)}{df(T_w^p)/dT_w^p} \quad (5)$$

Where; T_w^p is the past estimated wet-bulb temperature (ºC).

$$\frac{df(T_w)}{dT_w} = -\frac{dw_w}{dT_w} + (4.042 \times 10^{-4} + 5.816 \times 10^{-7})\left[T\frac{dw_w}{dT_w} - \frac{d(w_w T_w)}{dT_w}\right] \quad (6)$$

When the absolute difference between successive values of the wet-bulb temperature was less than 10^{-6}, the iteration was stopped.

Results

Dry and wet-bulb temperatures and RH in headspace

Figure 2 shows the dry and wet-bulb temperatures and RH in headspace of the warehouse for two years. The highest and lowest temperature of ambient air at the depot was in the early August and January. The local air RH was in the range of 60 to 95%. The average headspace temperatures were below 25°C and 23°C from May to October 2019 and 2020, respectively. The average headspace RH was 65% and 54% in 2019 and 2020, respectively. From May to October, the average wet-bulb temperatures of the ambient air were 23.8°C and 24.2°C in 2019 and 2000, respectively, while the headspace had average wet-bulb temperatures of 18°C and 15.7°C in 2019 and 2000, respectively.

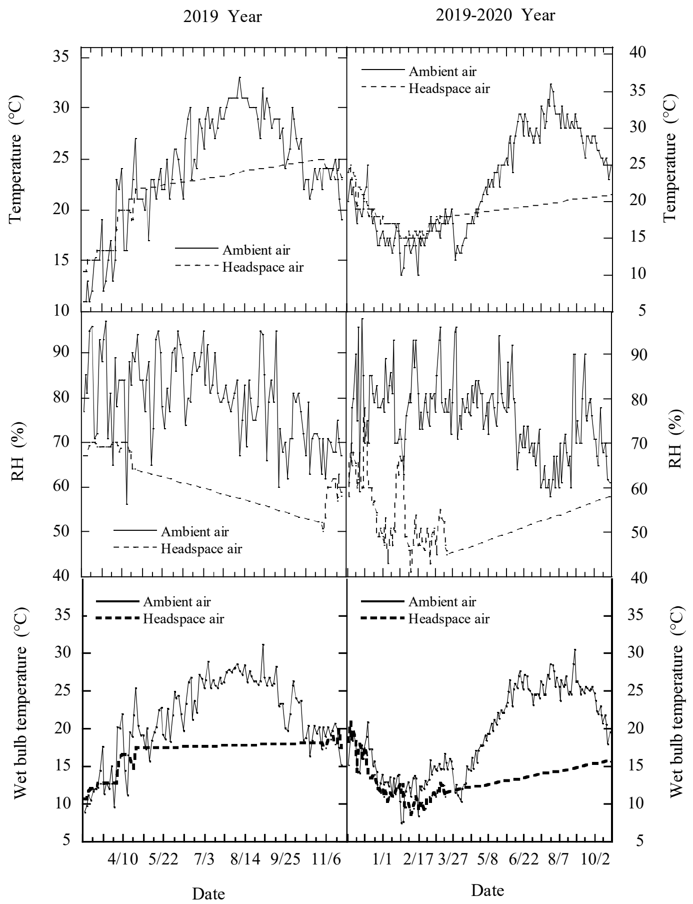

Fig. 2. Dry and wet-bulb temperatures and RH in headspace of the warehouse.

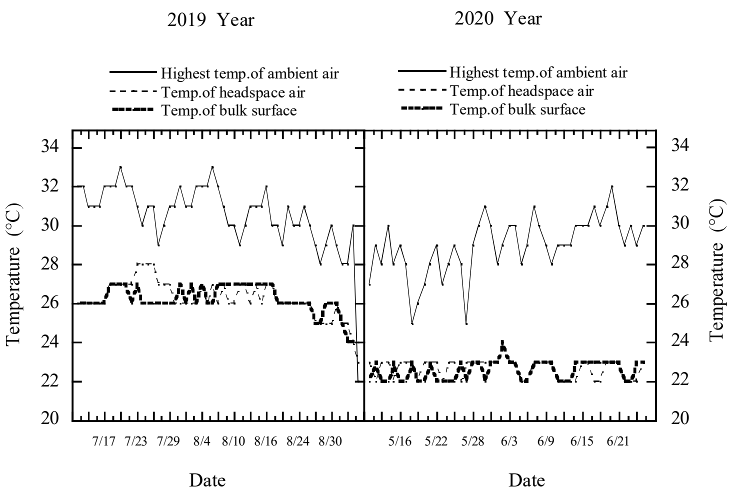

Fig. 3. Changes in the highest temperature of ambient air, temperature of headspace air and bulk surface of P27# warehouse when air conditioning was conducted.

Figure 3 shows the changes in the highest temperature of ambient air, temperature of headspace air and bulk surface of P27# warehouse for two years. These values during 12 July to 5 September, 2019 were 28-32°C, 24-28°C, and 24-27°C, respectively, while these were 25-32°C, 22-23°C, and 22-23°C during 11 May to 27 October, 2020, respectively.

The grain moisture content, air RH, and wet-bulb temperature in the grain bulk

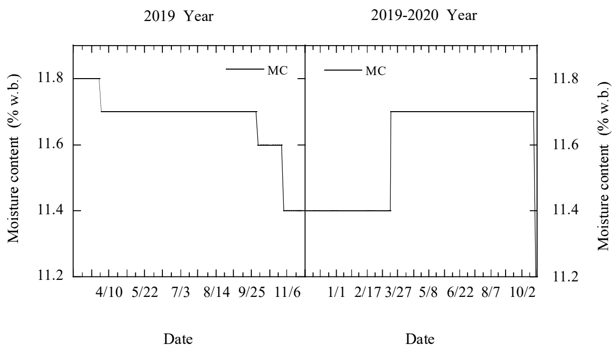

Fig. 4. Changes in moisture content of paddy bulk in the P27# warehouse.

The average moisture content of the paddy bulk was from 11.8% to 11.4% in 2019, and 11.7% to 11.2% in 2020 (Fig.4). The changes in dry and wet-bulb temperature and RH in the paddy bulk had the similar trends in 2019 (Fig.5).

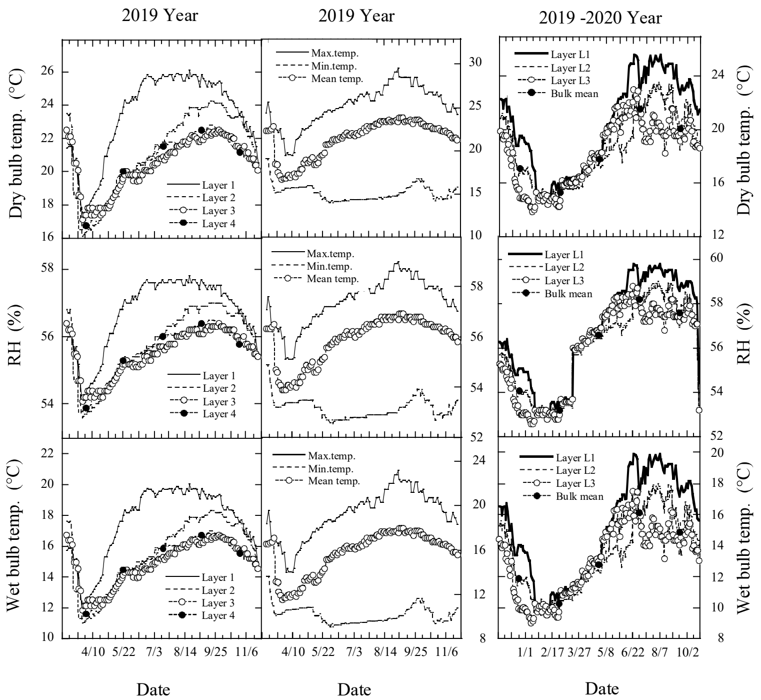

Fig. 5. The grain moisture content, air RH, and wet-bulb temperature in the grain bulk in 2019 and 2020.

From 1 April to 22 November, the dry and wet-bulb temperature and RH in Layer 1 of the paddy bulk were significantly higher than those of Layers 2, 3 and 4. Both Layers 3 and 4 had a similar dry and wet-bulb temperature and RH. The maximum, minimum, and mean dry and wet-bulb temperature and RH in the paddy bulk had the similar trends.

Changes in dry and wet-bulb temperature and RH in the paddy bulk in 2020 had the similar variation trends as 2019. During May to October, the average dry-bulb temperature, RH, and wet-bulb temperature in Layer 1 were 23.4°C, 58.9%, and 17.8°C, while in Layer 2 were 20.6°C, 57.7%, and 15.3°C, respectively. These average values in Layer3 and the whole bulk were 20.3°C, 57.6%, and 15.0°C, and 21.4°C, 58.1%, and 16.1°C, respectively.

Discussion

The depot in this study was located at Fuzhou, China, which has an average ambient air temperature higher than 28°C from May to October. The main technology to safely store indica paddy with 11.5% m.c. is to control insect pests. In 2019, fumigation was conducted from 29 April to 28 June, and air-condition cooling from 17 July to 15 October kept the temperature in Layer 1 of the paddy bulk below 26°C. Due to the poor thermal conductivity of the grain, the average dry-bulb temperature in Layers 2, 3 and 4 from August to September was below 24.5°C, 22.5°C and 22.5°C, respectively. The air relative humidity in Layers 1, 2, 3 and 4 was below 58%, which indicated that the paddy was dry. The wet-bulb temperatures in Layers 1, 2, 3, and 4 were below 20, 18.5, 17, and 17°C, respectively, which suggested a possible infestation of insect pests in Layers 1 and 2.

In 2020, the nitrogen treatment was conducted from 23 March to 25 September, and air-condition cooling from 11 May to 27 October kept the temperature in Layer 1 of the paddy bulk below 25°C. The average dry-bulb temperature in Layers 2, 3 and the whole bulk from August to September was below 23°C. The air relative humidity in the whole bulk was below 60%, which indicated a safe storage condition of the paddy bulk. The wet-bulb temperatures in Layers 1, 2, and 3 were below 20°C, 18.0°C, and 17°C, respectively. The fees for the fumigation and cooling in 2019 were 3.05 RMB per tonne of paddy. In 2020, the fees for the nitrogen treatment and cooling were 6.31 RMB per tonne.

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