Lowering paddy temperature with mechanical aeration guided by CAE model and aeration window

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Abstract

The moisture sorption isotherms of paddy kernels from Chinese fifteen varieties were fitted by an equilibrium moisture content (EMC) and equilibrium relative humidity (ERH) model called CAE with determination coefficient (R^2)＞0.993 and mean relative percentage error (*MRE*)＜5.3%. Parameters B_1 and B_2 in the CAE model for rough rice desorption and adsorption isotherms showed appreciable difference, consistent with a hysteresis between desorption and adsorption behavior in lower ERH. The measured sorption isotherms among japonica, indica and glutinosa rice had no difference, in accordance with the similar parameters of CAE model. It is concluded that the rough rice grains from different classes can be contemporaneously dealt with after harvest, but their desorptive and adsorptive behaviors should be differentiated from. The deduced CAE models for rough rice desorption and adsorption were respectively used to make curve graphs for searching equilibrium absolute humidity and equilibrium RH of rough rice grain with particular moisture at certain temperature. The variation of equilibrium absolute humidity of rough rice grain with temperature could clearly indicate the influence of a change in grain temperature on drying or moisture-adsorbing state of grains during aeration. To the purpose of decreasing grain temperature, or moisture content, or increasing grain moisture content, one can choose the curve graph for equilibrium absolute humidity of rough rice desorption or adsorption, and quickly make decision on grain aeration operation in a rough rice depot after referring to the absolute humidity of atmosphere at that particular RH and temperature. An intellectualized grain bulk detection, aeration window controlling, and CAE equilibrium moisture equation of paddy were used to instruct paddy aeration. An aeration window was constructed by the curves of paddy adsorptive equilibrium absolute humidity and the saturate absolute humidity. When the air status point lied within the aeration window, axial flow ventilator was turn on to circumvolve and decrease the grain temperature. When the air status point lied outside the aeration window, axial flow ventilator was turn off. During December 24th, 2012 to January 4th, 2013, this system was used to a paddy depot of 1340 t in subtropical region of Dianjiang, Chongqing, China and decreased grain temperature of 10.1°C within the accumulated 85 hours. The unit energy consumption was 0.015 kW h t^{-1}°C^{-1}, which is much lower than that (0.040～0.070 kW h t^{-1}°C^{-1}) of general temperature-decreasing aeration with the manual controlling ground cage ventilation. The paddy aeration course controlled by aeration window lowered energy consume 3 times than the ground cage ventilation.

Keywords: paddy, equilibrium moisture content, CAE model, sorption hysteresis, aeration window region, intellectualized mechanical aeration

1. Introduction

Rice is among the oldest of cultivated crops. History makes first mention of its being grown in China as early as 2800 B.C. Today nearly one half of the world's arable land is used for producing cereal grains, and about one-fifth of this is for the production of rice. China is the world's largest rice producer with annual production over 180 million tonne, and due to its large population, about 40 percent of its production is assigned to store longer periods in form of paddy with deterioration controlled largely through moisture content and temperature. In order to describe the process of drying, the ambient cooling of grain, and improving physical control in storage, a sound knowledge of the relationship between equilibrium moisture content (EMC) and equilibrium relative humidity (ERH) is essential (Pfost et al., 1976; Jayas & Mazza, 1991; Sun & Woods, 1993). The most useful way to define this relationship is fitting the data to a suitable equation (Sun & Woods, 1994; Li et al., 2009; Li & Wu, 2010). Many investigators have developed many equations, theoretically, semi-theoretically or empirically to describe the sorption isotherms of paddy. Sun (1999) analyzed 763 experimental data from eighteen source sets of rice EMC/ERH with four equations such as Modified Chung-Pfost (MCPE), Modified Henderson (MHE), Modified Oswin (MOE) and Strohman-Yoerger (STYE) and regarded STYE as the preferred fitting equation. However, there are few reports on fitting the EMC/ERH data of Chinese paddy varieties with a suitable equation.

To the pooled experimental EMC/ERH data of grain adsorption and desorption from the reference, some Chinese investigators have adopted a suitable equation to fit these data, and then applied this model (CAE equation) for a computer controlling grain aeration process (Wu, 1987; Wu and Li, 1998), but parameters of the CAE need to be updated with the EMC/ERH data of Chinese paddy varieties so that the equation could be widely accepted in grain depots. Thus, the aim of the present work is to determine the CAE parameters with our measured EMC/ERH data of fifteen Chinese paddy varieties and describe the usage of this CAE model in aeration decision-making, providing theoretical basis for grain aeration.

2. Materials and methods

2.1. Paddy samples and EMC/ERH experimental data

Seventeen Chinese paddy varieties were used in the sorption isotherm experiments. These paddy varieties, including three japonica, ten indica, and four glutinosa rices, were respectively collected from ten rice production regions in China during 2007 to 2010, as shown in Table 1. The rice kernels used for this study were intact, clean and plump. For adsorption experiment, the rice kernels were dried to the moisture content (m.c.) of 7-8% w.b. at 34.5°C in an oven, and then dehydrated by P_2O_5 solid in a dessicator to below 5% w.b. as being samples. For the samples of desorption experiment, the paddy varieties were re-moisturized from normal moisture to 20% w.b., and equilibrated at 4°C for two weeks.

The static gravimetric method, with the standard nine saturated salt (i.e. lithium chloride, potassium acetate, magnesium chloride, potassium carbonate, magnesium nitrate, cupric chloride, sodium chloride, potassium chloride, and potassium nitrate) solutions to maintain constant vapor pressure, was used to obtain nine equilibrium moisture contents at each of five constant temperatures (10, 20, 25, 30, and 35°C). The method for paddy EMC determination

was described in our recent reports (Li et al., 2010a; 2010b), five grams of sample were dried at 103 ± 1.0°C for 22-24 hours.

Table 1   Sample characteristics of fifteen varieties of paddy used in this study.

Sample No.	Variety	Classes	Grain type	Producing region	Harvest time
1	Hei9938	Japanica	elliptical	Helongjiang	Sep, 2007
2	Hei220	Japanica	elliptical	Helongjiang	Sep, 2007
3	Liao8433	Japanica	elliptical	Liaoning	Sep, 2007
4	Yixiang481	Indica	slim	Sichuan	Aug, 2007
5	Gangyou363	Indica	slim	Sichuan	Aug, 2007
6	Liangyou63	Indica	slim	Sichuan	Aug, 2007
7	Hubei501	Indica	slim	Hubei	Aug, 2007
8	Hubei527	Indica	slim	Hubei	Aug, 2007
9	Hunan xian09	Indica	slim	Hunan	Aug, 2009
10	Changde207	Indica	long elliptical	Jiangsu	Aug, 2008
11	Changde218	Indica	long elliptical	Jiangsu	Aug, 2009
12	Qianjiang 1	Indica	slim	Zhejiang	Aug, 2007
13	Guangzao xian	Early,indica	slim	Guangdong	Jun, 2007
14	Hunan nuo	Glutinosa	slim	Hunan	Aug, 2008
15	Jiangxi nuo	Glutinosa	slim	Jiangxi	Aug, 2008
16	Tuantuan nuo	Glutinosa	slim	Chongqing	Oct,2010
17	Jianjian nuo	Glutinosa	slim	Chongqing	Oct,2010

2.2. Analysis of paddy adsorption and desorption isotherm data with CAE equation

The CAE equation ERH and EMC model is,

$$ERH_w = e^{\dfrac{\frac{D}{222}\times\left(e^{\frac{B_1-M}{A_1}}-e^{\frac{B_2-M}{A_2}}\right)\times\left(1737.1-\frac{474242}{273+t}\right)+D\times\left(1-e^{\frac{B_1-M}{A_1}}\right)+202}{87.72}} \qquad (1)$$

Where ERH_w is the grain equilibrium relative humidity (%), M is the grain moisture content (% w.b.), t is grain temperature (°C). A_1, A_2, B_1, B_2, D are five parameters of CAE equation.

The adsorption and desorption isotherm data of fifteen paddy samples were respectively fitted to the CAE equation, using the non-linear regression procedure in SPSS 13.0 for Windows (SPSS, 2006), which minimizes the sum of squares of deviations between experimental and predicted data in a series of iterative steps. The goodness-of-fit of each equation was evaluated using determination coefficient (R^2), residue sum of squares (*RSS*), the standard error (*SE*), and mean relative percentage error (MRE). The R^2 was one of the primary criteria for selecting the best equation to fit the experimental data. In addition to R^2, the other statistical parameters, MRE as a percentage, *RSS* and *SE* were used to determine the quality of the fit. The equations (2) - (5) were used for calculating R^2, *RSS, SE*, and *MRE*, respectively.

$$R^2 = \sqrt{1 - \sum_{i=1}^{n}(m_i - m_{pi})^2 \Big/ \sum_{i=1}^{n}(m_i - m_{mi})^2}$$ (2)

$$RSS = \sum_{i=1}^{n}(m_i - m_{pi})^2$$ (3)

$$SE = \sqrt{\sum_{i=1}^{n}(m_i - m_{pi})^2 \Big/ (n-1)}$$ (4)

$$MRE = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{m_i - m_{pi}}{m_i} \right|$$ (5)

Where m_i is the experimental value, m_{pi} the predicated value, m_{mi} the average of experimental values, and n the number of observations. The fit of an equation is good enough for practical purposes when MRE is less than 10% (Aguerre et al., 1989).

2.3. Using CAE equation in a computer controlling grain aeration system

In a computer controlling grain aeration system, the parameters known CAE model (equation (1)) for paddy desorption and adsorption can be used to make curve graphs for searching the equilibrium relative humidity (ERH_w) of paddy kernels with particular moisture content at certain temperature. The following equation (6) can make curve graphs for searching the equilibrium absolute humidity of paddy kernels with particular moisture at certain temperature and the dewpoint temperature of grain at this absolute humidity.

$$EAH_w = e^{\dfrac{[\frac{D}{222} \times (e^{\frac{B_1-M}{A_1}} - e^{\frac{B_2-M}{A_2}}) + 0.9845] \times (1737.1 - \frac{474242}{273+t}) + D \times (1 - e^{\frac{B_1-M}{A_1}}) - 68.57}{87.72}}$$ (6)

Where EAH_w is grain equilibrium absolute humidity (mm Hg), M is grain moisture content (% w.b.), t is grain temperature (°C). A_1, A_2, B_1, B_2, D are five parameters of CAE equation.

The grain bulks' dewpoint temperature (DPT_w) was calculated by equation (7),

$$DPT_w = \frac{474242}{1872.7 - 89.1 \times \lg(EAH_w)} - 273$$ (7)

Where DPT_w is dewpoint temperature of grain bulks (°C), EAH_w is equilibrium absolute humidity of grain (mm Hg).

The atmosphere absolute humidity (AH_a) and dewpoint temperature (DPT_a) were respectively calculated with the following equations (8) and (9),

$$AH_a = 100 \times e^{\dfrac{87.72 \times lg(RH_a) + 0.9845(1737.1 - \frac{474242}{273 + t_a}) - 270.57}{87.72}}$$ (8)

$$DPT_a = \dfrac{474242}{\dfrac{474242}{273 + t_a} - 89.1 \times lg(RH_a) + 410.34} - 273$$ (9)

Where AH_a is atmosphere absolute humidity (mm Hg), RH_a is atmosphere relative humidity (%), and t_a is atmosphere temperature (°C), DPT_a is atmosphere dewpoint temperature (°C).

The relative humidity or absolute humidity in equations (1), and (6)-(9) was calculated on the basis of sea level atmospheric pressure. The values of DPT_w and DPT_a were used in characterizing whether dew condensation would occur with a decrease in temperature.

2.4. Aeration window controlling ventilator to circumvolve

2.4.1. The condition for aeration manipulation

This study was carried out at the Chongqing Dianjiang State Grain Stored Depot, Dianjiang, China. Dianjiang lies in a basin (30°N, 107°E, 450 meters of average altitude), belonging to subtropical humid monsoon climate. Its yearly average atmospheric temperature is 18°C, the diurnal temperature during June to August is over 40°C. This region has four distinct seasons with a warm winter and a hot summer. Thus, the mechanical aeration was used to decrease grain temp during October to December.

The experimental bin (No. 8,) with 31.4 m in length and 14.12 m in width has six ground cage-channels equipped with two axial flow ventilators, each ventilator responsible for three channels. The ratio of longest pathway to shortest pathway of air is 1.5. The local producing paddy of 1340 tonne with moisture 13.2% was garnered in October, 2010, with a 5.01 m of bulk height and 0.4% of foreign materials. The bin doors were closed, and its four windows in side top were opened. Aeration mode was negative pressure suction, the cold air entered bin through windows then passed through the layer of grain bulk, and exhausted from the ventilators. The ventilator (SFG4-2 type) has 320/220 Pa of full/static pressure, 11000 m³/h of air volume, and 2800 r/min of rotational speed, thus the calculated airflow rate is 16.4 m³/ht. In order to accurately decide the electricity consumption, an intelligent electric meter was used for aeration manipulation.

2.4.2. Change in aeration window with grain temperature

The aeration controlling system included the hardware such as ventilator-controlling module, digital humidity transmitter, new type temperature measuring cable, and protective filtrate cover for humidity sensor. The temperature-decreasing aeration operation started on 24th December of 2012. This system automatically detected grain-bulk temperature and the air temperature and relative humidity of upper space in the bin every 15 min, and also detected the air temperature and relative humidity of outside of the bin every 5 min. An aeration window was constructed by the curves of paddy adsorptive equilibrium absolute humidity and the saturate absolute humidity. When the air status point lied within the aeration window, axial flow ventilator was turn on to circumvolve and decrease the grain temperature. When the air

status point lied outside the aeration window, axial flow ventilator was turn off.

3. Results and discussion

3.1. Comparison of experimental sorption data between different paddy classes

The equilibrium moisture contents of desorption and adsorption at nine relative humidity ranged from 11.3% to 96.0% and five temperatures (10, 20, 25, 30, and 35°C) were respectively obtained for fifteen paddy varieties. All the isotherms of desorption and adsorption for paddy samples were sigmoidal in shape. At a constant ERH, both types of EMC decreased with an increase in temperature. A substantial difference was observed between the adsorption and desorption data at the same temperature. The desorption data was higher than the adsorption data except at high RH, and the moisture sorption hysteresis effect was more significant at lower ERH. Both width and span of the hysteresis effect tended to decrease with an increase in temperature.
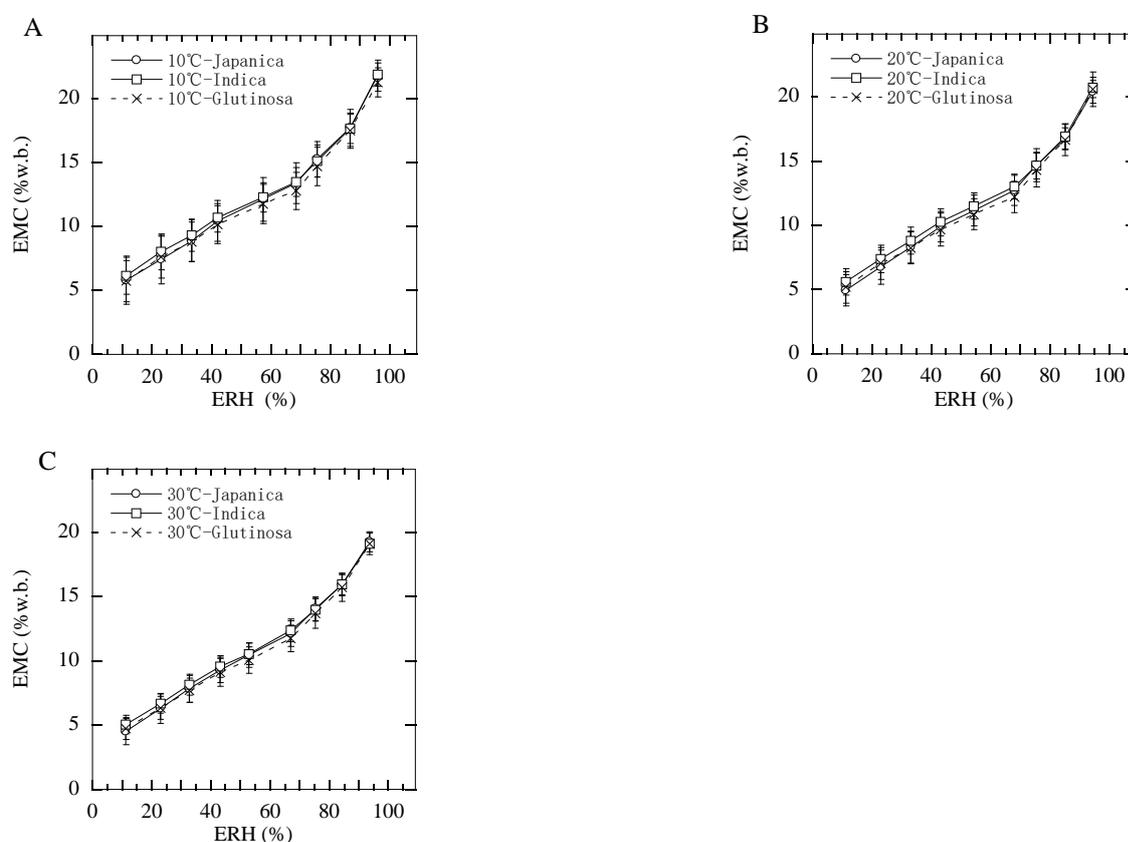

Figure 1 Comparison of the 10°C, 20°C and 30°C sorption isotherm among different paddy samples.

Figs. 1A,1B, 1C show the comparison of sorption isotherms at 10 °C, 20 °C, 30 °C for three paddy classes such as japonica, indica and glutinosa rice, respectively. The data were averaged from three japanica varieties, ten indica varieties, and four glutinosa varieties. Considering the standard deviation bars, no difference was found in sorption behaviors among three paddy classes. This result suggested the similar hygroscopic properties between different paddy classes.

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3.2. Fitting of CAE equation to experimental sorption data

The results of nonlinear regression analyses of fitting the CAE equation to the experimental sorption isotherm data of the first fifteen paddy varieties were shown in Table 2-3. The indices such as correlation coefficient (R^2), residue sum of squares (RSS), the standard error (SE), and mean relative percentage error (MRE) were given. All the R^2 values were high than 0.993, and the MRE values were less 5.33%. These results indicated that CAE equation fitted very well to the experimental data. In comparison of the parameters of CAE models between desorption and adsorption behaviors of paddy kernels, B_1 and B_1 showed apparent difference, agreeing with the significant hygroscopic property difference between desorption and adsorption isotherms at lower RH. However, each of five CAE parameters was similar between paddy classes (Table 4). Thus, we only consider the difference between paddy desorption and adsorption when CAE model is applied for a computer controlling grain aeration system.

Table 2 The CAE parameters for desorption data of fifteen paddy varieties.

Sample No	Parameters of CAE model					Statistical parameters			
	A1	A2	B1	B2	D	RSS	SE	R2	MRE%
1	5.098	4.929	6.893	5.258	207.161	124.0880	3.1022	0.9962	3.473
2	5.141	4.873	7.852	4.082	206.541	189.2913	4.7324	0.9942	4.636
3	4.531	4.991	7.481	3.573	206.248	188.2036	4.7051	0.9948	5.148
4	4.359	5.229	7.943	4.865	207.832	121.4760	3.0369	0.9962	3.516
5	3.847	4.112	7.461	4.222	199.855	131.3081	3.2827	0.9959	4.067
6	3.759	4.098	7.336	4.222	199.423	138.3461	3.4587	0.9957	4.563
7	4.259	5.051	8.319	4.508	205.142	159.2548	3.9814	0.9951	3.843
8	4.384	5.066	8.265	4.516	207.476	122.6097	3.0652	0.9962	3.657
9	4.389	4.851	8.924	4.175	205.337	145.9652	3.6491	0.9955	4.042
10	4.686	5.097	7.561	4.134	205.104	125.8939	3.1474	0.9961	3.871
11	5.219	5.109	5.944	4.324	208.788	82.1969	2.0549	0.9975	2.688
12	4.472	5.311	7.529	4.234	206.721	197.3367	4.9334	0.9939	4.212
13	4.356	5.101	8.907	4.106	207.274	176.7837	4.4196	0.9945	4.544
14	4.534	4.731	8.034	4.251	203.393	204.9559	5.1239	0.9937	5.323
15	4.327	4.836	7.062	5.107	204.389	157.3526	3.9338	0.9951	3.788
Mean Des	4.431	4.883	7.758	4.373	205.097	58.9278	1.4732	0.9982	2.174

Note: ^aDes, desorption; Mean des, the average of fifteen desorption data; *RSS*, residue sum of squares; *SE*, the standard error; R^2, determination coefficient; *MRE,* mean relative percentage error.

Table 3 The CAE parameters for adsorption data of fifteen paddy varieties.

Sample No	Parameters of CAE model					Statistical parameters			
	A1	A2	B1	B2	D	RSS	SE	R2	MRE%
1	4.557	4.475	4.899	3.431	201.594	109.4336	2.7358	0.9966	2.737
2	5.171	5.176	3.621	2.822	205.942	132.5132	3.3128	0.9959	3.001
3	5.032	5.437	4.124	2.617	206.826	130.4262	3.2607	0.9961	4.005
4	4.529	4.444	5.362	3.953	202.938	93.4753	2.3369	0.9971	3.016
5	4.301	4.221	5.845	3.771	204.119	90.5239	2.2631	0.9972	4.002
6	4.016	4.114	5.803	3.719	203.105	88.8690	2.2221	0.9973	3.836
7	3.995	3.976	5.569	4.064	200.935	195.6718	4.8918	0.9941	3.907
8	4.299	4.425	5.031	3.923	202.063	122.1569	3.0539	0.9962	3.737
9	4.451	4.674	4.615	3.605	204.373	133.3264	3.3332	0.9959	3.468
10	5.047	4.899	4.911	3.293	204.609	103.7186	2.5931	0.9968	3.255
11	5.036	4.851	5.591	4.116	206.071	99.9965	2.4999	0.9969	3.815
12	4.935	4.679	4.562	3.702	203.335	124.4777	3.1119	0.9962	2.939
13	4.728	4.561	5.627	4.531	204.514	125.7426	3.1436	0.9961	3.535
14	4.679	4.344	3.901	3.291	202.251	105.3109	2.6328	0.9967	2.799
15	4.675	4.436	4.018	3.157	203.903	173.1969	4.3299	0.9947	3.698
Mean ads	4.606	4.561	4.918	3.613	202.632	70.7154	1.7679	0.9978	2.353
Mean sorption	4.492	4.715	6.381	4.017	204.295	59.4719	1.4868	0.9982	2.106

Note: aads, adsorption; Mean ads, the average of fifteen adsorption data; Mean sorption, the average of thirty sets of sorption data; RSS, residue sum of squares; SE, the standard error; R2, determination coefficient; MRE, mean relative percentage error.

Table 4 Summary of the CAE parameters for the sorption of different paddy classes.

Paddy classes	Data sets	Parameters of CAE model					Statistical parameters			
		A_1	A_2	B_1	B_2	D	RSS	SE	R^2	MRE%
Japanic	3	4.824	4.989	5.927	3.611	205.386	79.4314	1.9858	0.9975	2.534
Indica	10	4.401	4.667	6.621	4.141	204.194	52.6293	1.3157	0.9984	2.069
Glutinosa	2	4.479	4.591	5.861	3.957	203.329	104.1151	2.6029	0.9968	2.823

Note: The data sets of glutinosa paddy include Hunan nuo and Jiangxi nuo.

To our knowledge, few studies have dealt with the difference in hygroscopic properties of different rice classes (Sun, 1999; Li & Wu, 2010; Li, et al., 2010b). The comparison of 10-30°C sorption isotherms and the parameters of CAE demonstrated that the identical hygroscopicity behaviors of grains was observed between paddy classes such as japanica, indica and glutinosa rice, evidencing that the paddy kernel from different classes can be concordantly dealt with during drying, storage and aeration.

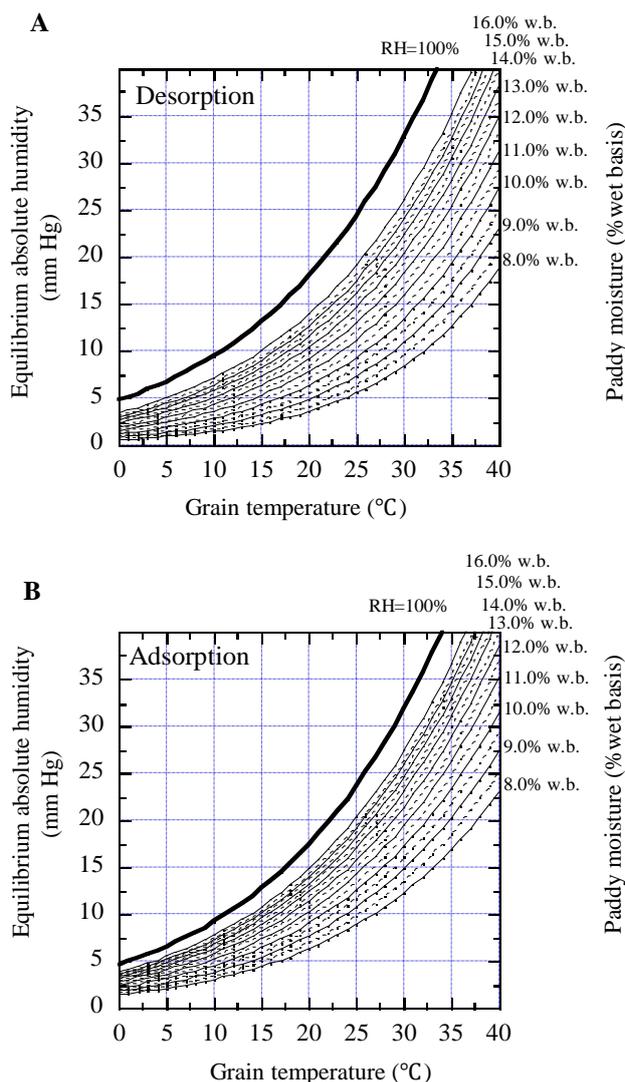*3.3. Using CAE equation in a computer controlling grain aeration system*

Figure 2 Curve graphs for searching the equilibrium absolute humidity of paddy grain with particular moisture at certain temperature and dewpoint temperature of the grain at this absolute humidity.

Figs. 2 and 3 are the curve graphs for searching the equilibrium absolute humidity and equilibrium relative humidity of paddy kernels with particular moisture at certain temperature, respectively. It is showed that the equilibrium absolute humidity of paddy kernels at certain moisture content drastically increased with an increase in grain temperature (Fig. 2), while the equilibrium relative humidity of paddy grain at the same moisture gradually increased with the increasing grain temperature (Fig. 3). Therefore, the change in equilibrium absolute humidity of paddy kernels at certain moisture content with temperature could clearly indicate the influence of a change in grain temperature on drying or moisture-adsorbing state of grains during aeration, and Fig. 2 is used for judging the aeration conditions. The desorption curves of the equilibrium absolute humidity (Fig. 2A) and the equilibrium relative humidity (Fig. 3A) of paddy kernels with particular moisture content at different temperatures are applied for decreasing grain temperature or moisture content by aeration. However, the adsorption curves

of the equilibrium absolute humidity (Fig. 2B) and the equilibrium relative humidity (Fig. 3B) of paddy kernels with particular moisture at different temperatures are used for suitably increasing grain moisture content by aeration and improving the process quality of grains.
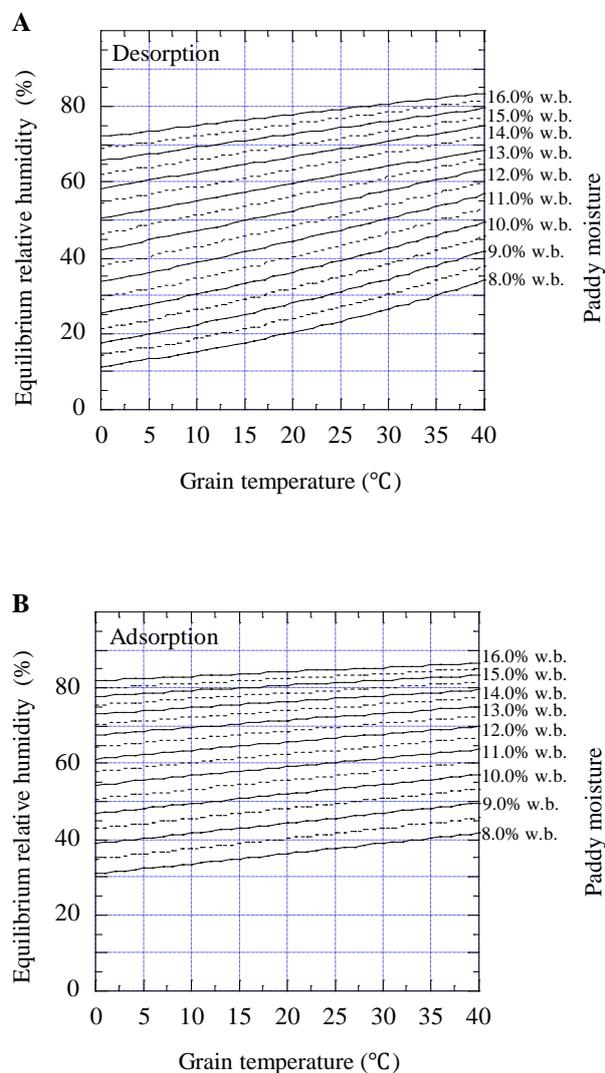

Figure 3 Curve graphs for searching the equilibrium relative humidity of paddy kernels with particular moisture at certain temperature.
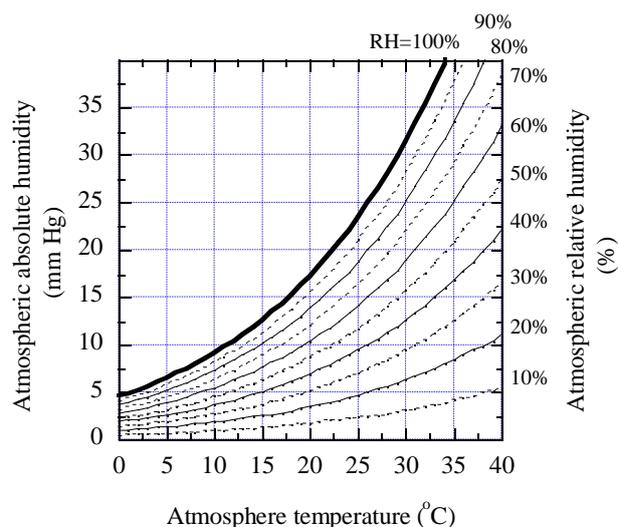
Figure 4 Curve graphs for searching the absolute humidity of atmosphere with particular relative humidity at certain temperature and dewpoint temperature of the atmosphere in this absolute humidity.

Fig. 4 is the curve graphs for searching the absolute humidity of atmosphere with particular relative humidity at certain temperature. In addition, the dewpoint temperature of grain or atmosphere can be respectively obtained from Figs. 2 or 4 by checking the corresponding temperature of a cross point between the curve of RH=100% saturated moisture and a temperature-axis parallelled line matching the absolute humidity of grain or atmosphere at particular temperature. As the Chinese Technical Protocol for Grain Aeration (Grain Industry Standard of the PRC, 2002) suggested, the condition for reducing grain temperature by aeration is that the equilibrium absolute humidity of atmosphere should be lower than that of grain stack; the temperature difference between grain stack and atmosphere is respectively +8°C at the beginning of grain aeration, and +4°C during grain aeration in all regions of China except for subtropical region, but in subtropical region both values are respectively +6°C and +3°C.

Give an example on reducing grain temperature in a south China paddy depot by aeration. Before grain aeration, the moisture and temperature of paddy stack were presumed to be 12.5% and 32.5°C, respectively. The temperature and relative humidity (RH) of atmosphere were postulated as 25°C and 80%. From Figs. 2A and 2B the equilibrium absolute humidity of paddy stack with 12.5% m.c at 32.5°C were searched to be 22.9 and 26.3 mm Hg for desorption and adsorption, respectively. The dewpoint temperatures of this grain stack were 24.6 and 26.9°C for desorption and adsorption, respectively. Searched from Figs. 3A and 3B, the corresponding equilibrium relative humidity of paddy stack was respectively 63.0% and 72.2% for desorption and adsorption. Absolute humidity and dewpoint temperature of the atmosphere with 80% RH at 25°C were 18.8 mm Hg and 21.3°C, respectively, directly obtained from Fig. 4. The comparative analyses show that the temperature difference between paddy stack and atmosphere was +7.5°C, higher than +6°C, a starting temperature difference for grain aeration in a depot. The absolute humidity of paddy stack for both desorption and adsorption was higher than that of atmosphere, thus, this kind of aeration would decrease the

grain temperature without increasing grain moisture. Despite that the dewpoint temperatures of grain stack were higher than the atmosphere temperature, they would quickly decreased below atmosphere temperature as the equilibrium absolute humidity of paddy stack was decreased by aeration. Thus, no dew condensation occurred within grain stack.

The deduced curve graphs for searching both equilibrium absolute humidity and equilibrium relative humidity of paddy kernels with particular moisture at certain temperature, and for searching the absolute humidity of atmosphere with particular relative humidity at different temperatures made one quick to decide whether grain aeration should be performed in a grain depot.

3.4. An example for change in aeration window with grain temperature

Table 5   Data detected by aeration system before aeration manipulation.

Layer of grain bulk	Highest grain temp. （°C）	Lowest grain temp. （°C）	Mean grain temp. （°C）	Mean bulk temp. （°C）	Temp in upper space （°C）	Outside air temp. （°C）	RH in upper space （%）	Outside air RH （%）
First	18.6	8.3	13.1					
Second	21.1	12.4	17.0					
Third	19.7	11.9	16.3	15.8	7.0	6.0	88.6	81.3
Fourth	20.1	12.3	16.9					

Note: The data was detected on 24th December of 2012.

From fig.5, the grain bulk had 13.2% of average moisture, 15.8°C of mean temperature, and 9 mm Hg equilibrium absolute humidity (ERH). The atmospheric temperature and RH were 6.0°C and 81%, respectively, corresponding to 5.8 mm Hg of ERH. Point B was the intersection between curves of the upper limit of aeration temperature and the saturate absolute humidity. Aeration window was a small area of BDFG, and the air status point lied within the aeration window, hence, aeration condition was meet and axial flow ventilator was turn on to circumvolve.
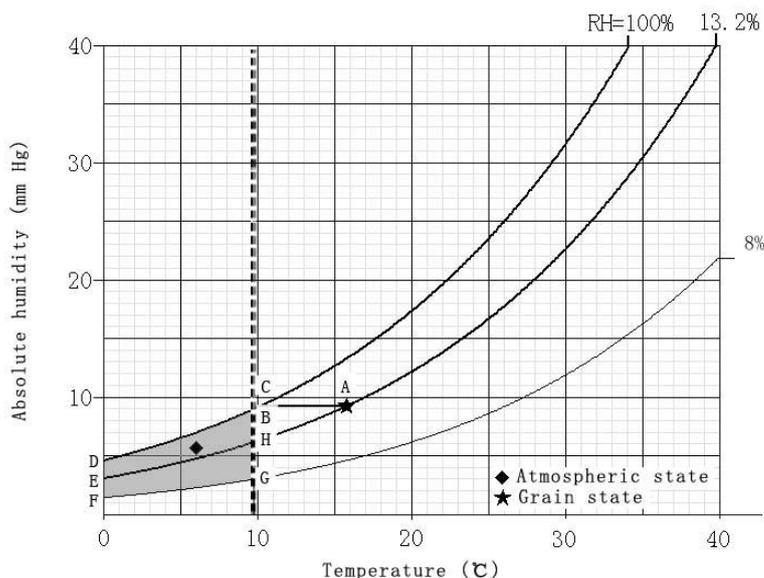
Figure5 A small area of aeration window before aeration manipulation (on 24th December of 2012).

From fig.6, on January third, 2013, the grain bulk had 13.2% of average moisture, 8.4°C of mean temperature, and 6 mm Hg equilibrium absolute humidity (ERH). The atmospheric temperature and RH were 3.8°C and 80%, respectively, corresponding to 4.9 mm Hg of ERH. Aeration window was a small area of BCDFG, and the air status point lied within the aeration window BCDEH, hence, aeration condition was still meet and axial flow ventilator continued to circumvolve.
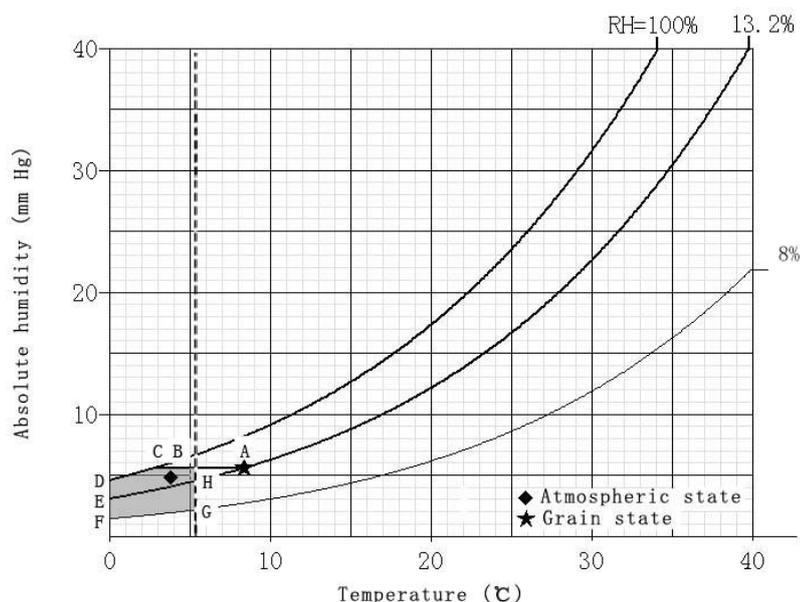

Figure 6 The small area of aeration window during aeration process (on January third, 2013).

From fig.7, on January 4th, 2013, the grain bulk had 13.2% of average moisture, 5.7°C of mean temperature, and 4.9 mm Hg equilibrium absolute humidity (ERH). The atmospheric

temperature and RH were 3.1°C and 85.4%, respectively, corresponding to 5.0 mm Hg of ERH. The grain ERH nearly equaled to that of outside atmosphere. Aeration window was a small area of BCDFG, and the air status point moved out the aeration window BCDFG, hence, aeration condition was not meet and axial flow ventilator was turned off. The aeration manipulation in no. 8 bin was ended on January 4th, 2013.
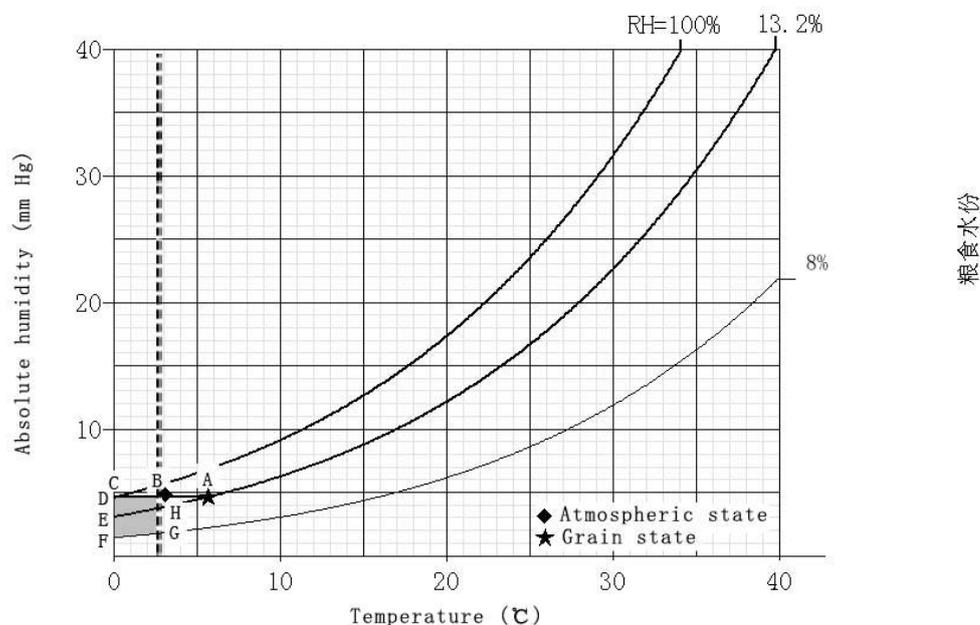

Figure 7 The air status point moved out the aeration window BCDFG (on January 4th, 2013).

Table 6 The data detected by aeration system after aeration completeness.

Layer of grain bulk	Highest grain temp. (°C)	Lowest grain temp. (°C)	Mean Grain temp. (°C)	Mean Bulk temp. (°C)	Temp In upper space (°C)	Outside air temp. (°C)	RH in upper space (%)	Outside air RH (%)
First	4.9	3.3	4.2					
Second	6.5	3.8	4.7					
Third	9.1	3.6	5.2	5.7	3.2	3.1	86.7	85.4
Fourth	17.5	3.5	8.6					

Note: The data was detected on January 4th, 2013.

3.5. Analysis of energy consumption in temperature-decreasing aeration

In this study, the aeration duration was 8 days, accumulative total time of aeration was 85 h, the factual motion time of axial flow ventilator was lower 3.5 days, and the mean temperature of grain bulk decreased 10.1°C. The electric meter showed the total power consumption was 205 degree, thus the unit energy consumption was 0.015 KW h t^{-1}°C^{-1}. At the similar aeration condition, the traditional manually controlling temperature- decreasing aeration manipulation had 0.040～0.070 KW h t^{-1}°C^{-1} of the unit energy consumption.

4. Conclusion

4.1 The moisture sorption isotherms of paddy kernels from Chinese fifteen varieties were well fitted by CAE model. The hysteresis between desorption and adsorption behavior of paddy at lower RH was also shown by the appreciable difference in parameters B_1 and B_2 of CAE model fitting paddy desorption and adsorption isotherms. The measured sorption isotherms between paddy classes like japonica, indica and glutinosa had no difference, in accordance with the similar CAE model parameters.

4.2 The deduced CAE models for paddy adsorption and desorption were respectively used to make curve graphs for changes in equilibrium absolute humidity and equilibrium RH of paddy kernel with temperature. The variation of equilibrium absolute humidity of paddy grain with temperature could clearly indicate the influence of a change in grain temperature on drying or moisture-adsorbing state of grains during aeration. Referring to the curve graphs for the change in absolute humidity of atmosphere at particular RH with temperature, one can quickly make decision on grain aeration operation in a paddy depot.

4.3 An intellectualized grain bulk detection, aeration window controlling, and CAE equilibrium moisture equation of paddy were used to instruct paddy aeration. An aeration window was constructed by the curves of paddy adsorptive equilibrium absolute humidity and the saturate absolute humidity. When the air status point lied within the aeration window, axial flow ventilator was turn on to circumvolve and decrease the grain temperature. When the air status point lied outside the aeration window, axial flow ventilator was turn off.

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