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Rough Rice Grain Cooling Using Vaporization of Temporarily Deposited Surface Water

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Abstract-A method of grain cooling by vaporizing temporarily deposited surface water on rough rice was tested in this study. The surface water was deposited by ventilating rough rice grains with saturated air (humidification) for predetermined time periods (3.5 and 7 minutes). After humidification, evaporative cooling was achieved by ventilating rough rice grains with ambient air. The data were collected using a bed of rough rice (height 0.15m) in a 0.11m diameter circular bin. Temperature and the relative humidity of the ambient air during the experiment time was 30±1°C and 65±1%. The grain temperature was monitored at 0.025, 0.075 and 0.125m heights from the bottom of the rough rice column using thermocouples. The temperature and relative humidity of air at the inlet, outlet and the ambient were recorded. The enthalpy values of air and grain and the temperature drop of grains were calculated for the two humidification times of 3.5 and 7 minutes using an iterative procedure. The 7 minutes humidification led to an average temperature drop of 3.3°C compared to 3.5 minutes humidification in which the drop was 2.1 °C. The 7 minutes humidification has an advantage in bringing down the grain temperature significantly ($P<0.001$; 95% confidence interval of the difference was 0.57 to 1.58°C; coefficient of variance was 4.58%).

Index Terms- Grain cooling, humidification, storage, vaporization

I. Introduction

The temperature and moisture content of grains are considered to be the most important factors affecting grain quality during storage or aeration; ideally moisture of grain should not be gained or lost during storage [1]. The effect of storage conditions on the storability of a range of crops including cereals have been documented by Bass [2]; Copeland and McDonald[3]. Grain temperature is the major stored grain management tool that regulates the insects and molds in storage. The physiological deterioration and biological risks of stored product can be well controlled by chilled aeration [4]. Ambient aeration systems could be used to lower the grain temperature within several degrees of the minimum ambient temperature while chilled aeration permits the short to long term storage regardless of the ambient conditions [5].

The temperature exceeding 25°C and relative humidity greater than 65% have been identified as harmful for storage of many seeds [6]. The temperature and relative humidity in most ambient seed stores in the dry zone of Sri Lanka are well above these values and are harmful for storage of seeds of many crops. Mettananda[7] has evaluated the effect of storage environment and packing method on the viability of seed paddy. Fernando *etal*. have conducted a survey on eight indigenous on farm grain storage systems in Sri Lanka and the estimated postharvest loss is about 8% [8]. Many storage structures and different techniques of grain storage have been tried in Sri Lanka during the past decades. The quality change and mass loss of paddy during airtight storage in a ferro-cement bin has been tested in Sri Lanka [9]. The possibility of storing paddy in hermetically sealed plastic liners has also been evaluated [10].

The cooling of dry grain during storage by ventilation with ambient air has received increasing attention in recent years. If ambient aeration is used in tropical countries, the grain temperature in silos generally remains above 25°C [11]. This frequently results in pest and fungal infestations requiring chemical control. Evaporative cooling is a physical phenomenon in which evaporation of a liquid, typically into surrounding air, cools an object or a liquid in contact with it. The cooling is provided by the evaporative heat exchange which takes the advantage of the principle of latent heat of evaporation in which tremendous heat is exchanged when water evaporates [12]. No application of evaporative cooling system to the cooling or chilling of grains has been found in literature [13]. In this research, a method of grain cooling by vaporizing temporarily deposited surface water on rough rice grains was tested. The moisture was deposited on grains by ventilation with saturated air (humidification). The deposited water was then evaporated by subsequent ambient air ventilation. When the ambient air is blown across the grain bed, the previously deposited moisture on the grain surface get evaporated absorbing the latent heat of vaporization from the grain lowering the grain temperature.

II. MATERIALS AND METHOD

The rice variety of BG 354 harvested from Dodangolla Research Farm, Faculty of Agriculture, University of Peradeniya, Sri Lanka in 2014 Yala season (April to August) was used for the experiment. The moisture content of rough rice at the time of harvest was 23% w.b. The rough rice samples were manually threshed by stripping the grains from the panicle and shade dried for 03 days until the moisture content reached to 12% w.b. The bulk sample was packed in polyethylene sacks and stored at 5°C until time for the tests. The samples were kept at room temperature for 10 hours before starting each experiment to bring the grains to the ambient temperature. This experiment was designed to test the effect of humidification duration on grain temperature drop. Two humidification durations; 3.5 minutes (Treatment I) and 7 minutes (Treatment II) were tested with three replicates each. The duration of evaporative cooling was 10minutes for all the replicates. Saturated air for humidification was produced by saturating ambient air with water vapor produced by an ultrasonic humidifier (Mammy, MUH 4400, Japan). Evaporative cooling of grains was achieved by ambient air forced ventilation.

A rough rice column having 0.11m diameter and 0.15m height was used for the study and the experimental setup is illustrated in the Figure 1. The ambient temperature and the temperature of air at the inlet and outlet, were measured using 'T' type thermocouples and recorded at 2 seconds intervals. The grain temperature was measured by 'T' type thermocouples inserted in to the center of the grains and placing those grains at 0.025 (L1), 0.075 (L2), 0.125m (L3) heights in the sample bed. The grain temperature was recorded continuously throughout the test period at 2 seconds intervals. The ambient, inlet and exhaust air relative humidity were measured using relative humidity sensors (TDK: CHS-UGR, Japan) at 5 seconds intervals. The moisture content was measured at the beginning and at the end of the tests by drawing 10 g samples from each layer. All the moisture content measurements were made by air oven dry method by drying whole grains sample at 135°C for 24 hours [14].

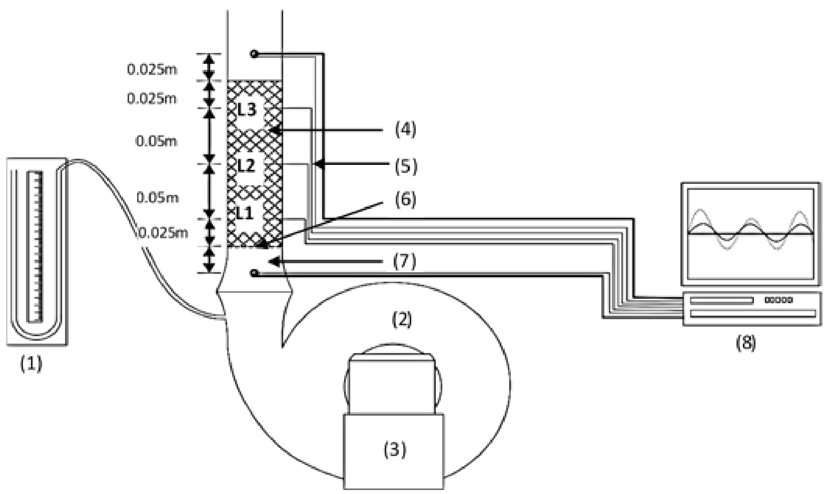

FIGURE 1: Experimental set up for rough rice grain cooling by evaporative cooling.

Thermodynamic properties of air and the grains

The enthalpy difference of the whole process ofhumidification and dehumidification is contributing to the change in grain temperature. Therefore the thermodynamic properties of air entering and leaving the rice column and the thermodynamic properties of grains were calculated for studying the contribution of humidification time on grain cooling. The enthalpy values of air and sensible heat values of grains were calculated for 10 seconds intervals and numerically integrated to get the cumulative values for the humidification and evaporative cooling durations separately for comparison purposes. The sensible heat gain of paddy,Q_m (kJ) is calculated using the equation 01.

$$Q_m = M\left(C_{ps}\right)(T_o - T_i) \qquad (1)$$

Where, M is the mass of rough rice (kg), $T_o$is the final temperature (°C) and $T_i$is the initial temperature (°C). The specific heat capacity of rough rice, C_{ps} ($kJ \cdot kg^{-1} \cdot K^{-1}$), in the above equation is calculated using the following expression where,M_w is the moisture content in % wet basis [15].

$$C_{ps} = 0.9214 + 0.545M_w \qquad (2)$$

The moist air specific enthalpy, h ($kJ \cdot kg^{-1}$ dry air) is calculated using the following equation [16].

$$h = 1.006t + W(2501 + 1.805t) \qquad (3)$$

Where, t is the dry bulb temperature (°C) and W is humidity ratio expressed as follows,

$$W = 0.62198\frac{P_w}{P - P_w} \quad (4)$$

Where, P is the total mixture pressure of dry and moist air (Pa), regarded as the atmospheric pressure (101.325 kPa) and P_w is the partial pressure of water vapor. The relative humidity of air, φ is expressed as follows,

$$\varphi = \frac{P_w}{P_{ws}} \quad (5)$$

Where, P_{ws} is the saturation pressure of liquid water (Pa) and is given by the following equation for the temperature range of 0 to 200 °C, in which T is the absolute temperature [16].

$$lnP_{ws} = \frac{C_8}{T} + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}lnT \quad (6)$$

Where;

$C_8 = -5.8002006 \times 10^3$,

$C_9 = 1.3914993$,

$C_{10} = -4.8640239 \times 10^{-2}$,

$C_{11} = 4.1764768 \times 10^{-5}$,

$C_{12} = -1.4452093 \times 10^{-8}$,

$C_{13} = 6.5459673$.

The data presented in the Table 1 were calculated using a method of numerical integration (trapezoidal method) for all the replicates in the two treatments of 3.5 and 7 minutes humidification durations. The data were subjected to two sample T-test using MINITAB statistical software (version 17) and the mean, standard deviation, coefficient of variance (CV) and the significant probability (P) values were calculated.

III. RESULTS AND DISCUSSION

According to the Figure 2, the grain temperature increased with humidification due to the release of the latent heat of condensation and heat of adsorption of water. The latent heat of condensation is partly used for the temperature rise in the grain and the rest is lost to the air by convection. Saturating the inlet air by adding water droplets reduced the inlet air temperature and this helps positively in reducing the grain temperature rise due to the release of latent heat of condensation. When the surface water deposition stopped, it started to vaporize surface water taking the latent heat of vaporization from the grain. The total sensible heat gain of grains is lower at $P<0.001$ in 7 min humidification compared to 3 min humidification (Table 1). Possibility of convective loss of heat from the grains is higher in 7 min humidification and helps in lowering the grain temperature rise due to heat of condensation and heat of adsorption of water. Since some of the energy of condensation already dissipated to the air stream by convection, vaporizing the same amount of water (as condensed) reduced the grain temperature below its initial temperature.

Table 1 presents the mean, standard deviation and coefficient of variance for all the parameters of each treatment as well as the confidence interval (CI) for the difference (μ2-μ1). The CIs indicate that the difference between the two treatments were significantly different for all the parameters except for the enthalpy of air entering the grain bed during evaporative cooling, enthalpy gain of air during evaporative cooling and the total sensible heat loss of paddy during evaporative cooling.

The main interest was on the variable "Grain temperature drop" where the difference is significant at $P<0.001$. Even with 3 observations for a treatment the difference is highly significant, while the CV% is low (4.58%). The 95% CI for the difference between grain temperature drop for 7 and 3.5 min humidification is in the range 0.57 to 1.58°C. This implies that compared to 3.5 min humidification, 7 min humidification has an advantage in bringing down the grain temperature significantly. The 7 min humidification led to an average grain temperature drop of 3.3°C compared to 3.5 min humidification in which the drop was only 2.1°C. The grain temperature drop is related to the enthalpy of air leaving the grain bed during evaporative cooling. The 95% CI of the difference in this parameter was 7.4 to 22kJ. The higher heat loss by the grain during evaporative cooling can be the reason for the greater drop in grain temperature for treatment II (7 min humidification). The differences were highly significant and the CV% is low for the parameters, enthalpy of air entering and leaving the grain bed and the total sensible heat gain of grains during the humidification phase. Therefore it can be concluded that the 7 min humidification positively contribute to the grain cooling effect in all parameters.

TABLE 1: Comparison of different parameters for the two treatments of 3.5 min and 7 min humidification duration.

Description	Treatment I 3.5 min humidification		Treatment II 7 min humidification		P value[a]	95% CI[b]	
	Mean±SD	CV%	Mean±SD	CV%		L	U
Enthalpy of air entering the grain bed (kJ)during humidification	92.8±4.0	4.3	167.2±4.6	2.8	0.001	64.7	84.2
Enthalpy of air leaving the grain bed (kJ)during humidification	32.2±0.9	2.9	62.9±0.2	0.3	0.001	29.2	32.3
Enthalpy gain (kJ) of air during humidification	60.6±3.2	5.3	104.3±4.7	4.5	0.001	52.8	34.6
Total sensible heat gain of paddy (kJ) during humidification	15.5±0.5	3.0	4.7±0.6	13.6	0.001	11.9	9.4
Initial grain temperature rise (°C)	1.9±0.06	3.3	0.6±0.07	12.7	0.001	1.4	1.1
Enthalpy of air entering the grain bed during evaporative cooling (kJ)	174.4±8.2	4.7	192.2±10.6	5.5	0.084	Not significant	
Enthalpy of air leaving the grain bed during evaporative cooling (kJ)	83.2±4.2	5.1	97.9±1.1	1.1	0.005	7.4	22.0
Enthalpy gain of air during evaporative cooling (kJ)	91.2±5.0	5.5	94.2±9.6	10.2	0.652	Not significant	
Total sensible heat loss of paddy during evaporative cooling (kJ)	32.0±4.4	13.7	30.7±2.2	7.3	0.687	Not significant	
Grain temperature drop (°C)	2.1±0.11	5.2	3.3±0.2	4.5	0.001	0.9	1.5

[a] Significant P value for the difference
[b] 95% confidence interval for the difference μ_2- μ_1; L=Lower boundary of CI, U= Upper boundary of CI

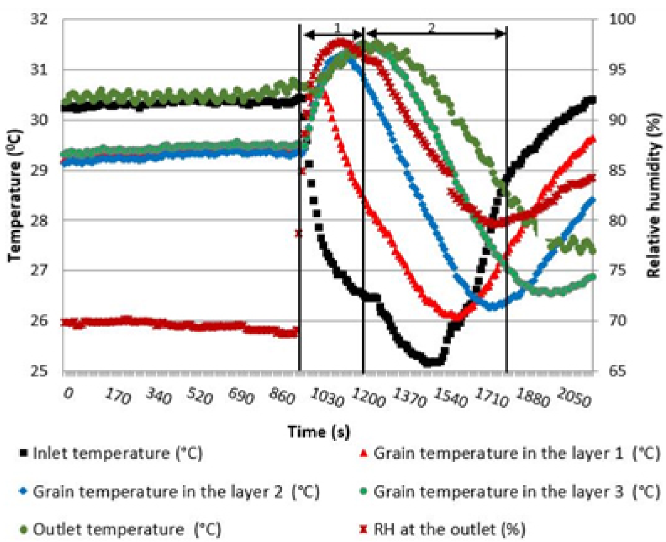

FIGURE 2: The observed rice grain temperature in the three layers, inlet and outlet air temperature and the outlet RH during 3.5 minutes humidification (1) followed by 10 minutes evaporative cooling (2).

CONCLUSION

The tested rough rice grain cooling mechanism by vaporizing temporarily deposited surface water proved to be successful. On average a temperature drop of 2.1°C and 3.3 °C could be achieved when rough rice was subjected to 3.5 and 7 minutes humidification followed by 10 min dehumidification respectively when the temperature and the relative humidity of the ambient air during the experiment time was 30±1 °Cand 65±1% respectively. Ambient air temperature and relative humidity determines the rate of vaporization of deposited water and thereby the grain temperature drop.

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