EFFECTS OF RESTING PERIODS, AIR TEMPERATURES, AND AIR VELOCITIES ON FREE-FALL PADDY DRYER PERFORMANCES

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Abstract

The free-fall paddy dryer has been recently invented and patented by the second author. This paper reports the results of the investigation into the drying rates, the primary specific energy consumption of the dryer, and the resulting rice quality including head rice yields and whiteness of milled rice. The following drying conditions were used: air temperatures of 40, 60, 100, 130, and 150°C; drying air velocities: 1, 2, and 3 m s^{-1}; and rest periods: 0, 1, 2, and 4 min. Test results showed that the dryer consumed quite low energy, of the order of 2-4 mega joules per kilogram of water evaporated. In addition, the rest periods higher than 1 min could maintain the amount of head rice yields and whiteness levels similar to those of the reference sample (ambient drying). Thus, high milled rice qualities and low energy consumption could be achieved in a single drying process.

Keywords: Free-fall dryer, energy consumption, milled rice quality, glass transition temperature

Introduction

A new grain dryer has been recently invented and patented (Department of Intellectual Property of Thailand, 2007) and has been experimentally proven to be fast, energy efficient, and capable of yielding high product qualities (such as head rice yield and whiteness) as compared to other types of dryers such as the fluidized bed dryer and the spouted bed dryer (Chitsomboon *et al*., 2006).

The drying machine is shown schematically in Figure 1. The heart of the dryer is the vertical drying column within which the grain and the drying air flow in opposite directions; the grain flow is

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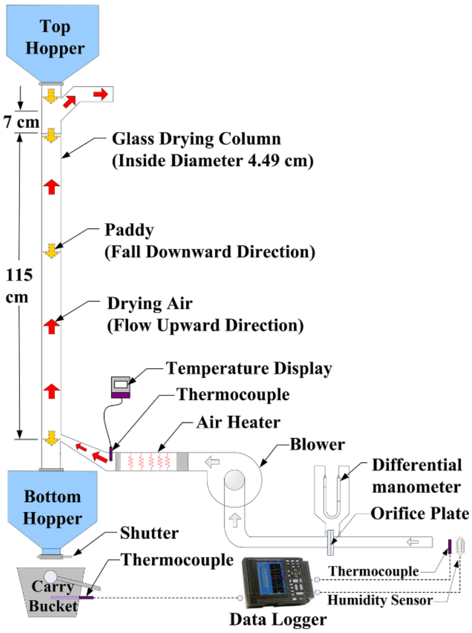

Figure 1. Schematic of the laboratory-scale free-fall dryer

downward in a free-fall manner while the air flow is upward under a driving force from an air blower. A high relative velocity between the grain and the air, a short contact time, and a rest period between 2 adjacent drying passes through the drying column contribute to the uniqueness and the high efficiency of this dryer. Its relatively simple operating procedure and low requirement of equipment should help reduce the investment and the operating costs of the dryer. Further detailed studies on the effects of the various controlling parameters for this dryer are needed to evaluate its applicability. Past researches have confirmed that drying paddy rice with a too high drying rate can cause paddy kernels to fissure (Li *et al.*, 1999; Jia *et al.*, 2002; Poomsa-ad *et al.*, 2005, Tohidi *et al.*, 2017), resulting in low head rice yields. Fissuring is mainly caused by a too high moisture gradient that occurs within the grain during a fast-drying process (Li *et al.*, 1999; Poomsa-ad *et al.*, 2005; Dong *et al.*, 2010). A high moisture gradient, however, is required if the moisture is to be rapidly diffused from the inside of the grain to its surface. It was found that a fast drying rate such as that which occurs in the fluidized bed dryer caused fissuring after a certain drying time had lapsed (Poomsa- ad *et al.*, 2005; Prachayawarakorn *et al.*, 2005a). A tempering process, employed just at the right time, could help alleviate the fissuring problem while also helping to improve the drying rate (Poomsa-ad *et al.*, 2002; Prachayawarakorn *et al.*, 2005a; Nishiyama *et al.*, 2006; Aquerreta *et al.*, 2007; Golmohammadi *et al.*, 2015); but the practice adds additional cost and time. A fast drying machine without the fissuring problem and without the additional procedures (such as tempering) is thus highly desirable. To this end the spouted bed dryer seems to be an ideal candidate but it was found that this dryer has a drawback in that the very high air velocity (of the order of 12 m s^{-1}) is not fully utilized and thus must be partially recycled through a rather complicated control algorithm (Madhiyanon *et al.*, 2002); its secondary power requirement could also be expected to be high because of fluid friction in the high velocity flow.

Whiteness is another desirable characteristic for milled rice; its lack is believed to be due primarily to the paddy being exposed to a high temperature for a long period of time (Prachayawarakorn *et al.*, 2005a). Due to its unique characteristics, the free-fall dryer could produce a relatively cool paddy (hence with a possibility for good whiteness) since the heat transfer process occurs in an opposed flow manner with a very short period of contact time. For the free-fall dryer in this study, it was expected from its inception that this newly invented dryer, despite its fast drying rate, would not suffer from kernel fissuring because of a low contact time between the paddy and the hot drying air (about 0.5 s per drying pass in this study). In addition, the contact periods were alternated with a relatively long resting period (varied from 0 to 480 times of the contact time per drying pass in this study) which helped in the relaxation of moisture and temperature gradients in the paddy kernel (much like the tempering process in other drying machines). High drying rates were expected since the moisture and heat transfer processes occur through very high moisture and temperature gradients near the grain surface at all times. The rest periods which come naturally with this dryer help to promote a diffusion of the moisture from inside the kernel to replenish the deficient moisture at the surface in order to be carried away by the heated air during the next drying pass.

In this study the effects of rest periods, air velocities, and air temperatures on the drying rates and energy consumptions of the dryer were investigated. Furthermore, the paddy was examined for its quality in terms of head rice yields (HRYs) and whiteness.

Free-Fall Paddy Dryer

From the schematic as depicted in Figure 1, the heated drying air flows through the vertical drying column in an upward direction which is opposite to the downward free-fall direction of the grain being dried. Grain falls by gravity force from the top hopper into the drying tube without obstruction from the frontal grain layer (unlike the stack flow pattern). This is the main design point that differs from a conventional counter flow grain dryer. As a result, grain velocity and grain bulk porosity inside a free-fall grain dryer will be higher than a conventional counter flow grain dryer. The high porosity of the column of the free-falling grain (about 0.96 to 0.98 in this study), together with the high relative velocity (about 4 to 6 m s^{-1} in this study) between the air and the grain help enhance the heat and moisture transfer processes; churning and turbulence provide further transfer enhancements. Therefore, moisture content uniformity of the grain bulk at the end of the drying process could be expected while it is not found in fixed deep bed drying (Sarker *et al.*, 2014). The contact time between the paddy and the air is typically very short, only about 0.5 s for the 1.15 m long drying column of this particular laboratory-scale model. Despite the short contact time it is expected that in an industrial scale dryer, where the drying column length is typically 5 m, the exhausted air would be more fully utilized in terms of its drying potential which needs to be studied further. Note that partial recycling of exhausted air is necessary for an economical operation of an industrial fluidized bed paddy dryer (Prachayawarakorn *et al.*, 2005b; Sarker *et al.*, 2015b). This free-fall dryer has a built-in rest period, much like the spouted bed dryer, since the grain leaving the drying column has to wait in the storage bin for the conveyor to carry it into the next round of drying in the drying column. The duration of this rest period will depend on the size of the storage bin and the feed/conveying rate. Past researches for other drying techniques have shown that a rest period (usually in a tempering environment) could help increase head rice yields (Li *et al.*, 1999; Chua *et al.*, 2003) as well as drying rates (Cnossen *et al.*, 2002; Poomsa-ad *et al.*, 2002; Nishiyama *et al.*, 2006). But it should be noted that this bin rest is not exactly the same as a tempering rest since the environment is not controlled to be air-tight and adiabatic.

Glass Transition Temperature Concept

Glass transition temperature (Tg) is defined as the temperature at which a polymer undergoes a distinct transition from a “glassy” to a “rubbery” state. Many physical properties change at this state of transition (Ferry, 1980), such as specific heat, specific volume, expansion coefficients, and viscoelasticity.

A rice kernel can be regarded as a composite material consisting of several different biopolymers, including starch and proteins with moisture as a plasticizer. Starch is the main constituent of rice. It is composed of 2 polysaccharides, amylose (crystalline structure) and amylopectin (amorphous structure). If the rice kernel temperature is below the Tg, then the starch exists in a glassy state, the starch granules are compact, and water associated with the starch is relatively immobile. Thus, the rice kernel has a low expansion coefficient, low specific volume, and low diffusivity. As the kernel temperature increases above the Tg, the starch transforms to a rubbery state whereby its macromolecular structures have greater free volume, and thereby water in the starch is more mobile. So, the rice kernel has a higher expansion coefficient, higher specific volume, and higher heat and mass diffusivities (Cnossen *et al*., 2002; Sun *et al*., 2002). During a typical paddy drying and tempering, the temperatures of the grain often pass through the Tg (35-60ºC) (Perdon *et al*., 2000; Li *et al*., 2016). Figure 2 shows the Tg relationship (state diagram) for the long-grain rice variety Drew as measured by Seibenmorgen *et al*. (2004), indicating that the Tg is inversely related to the moisture content. The solid line represents an approximated Tg value while the dash lines represent the upper and lower bounds at a 95% confidence level. The starch composition of the rice varieties Drew and Chainat1 are similar in amylose content (20.8% and 19.76%, respectively) but some differences exist in amylopectin (68.3% and 75.17%, respectively) (Patindol and Wang, 2002; Wansuksri et al., 2005). Therefore, the state diagram of Drew was adopted in this study to analyze the glassy or rubbery state of Chainat1.

The glass transition concept is very useful in helping to explain trends in the drying rate and fissure formation in paddy drying. The change in volumetric expansion and specific volume during the glass transition were found to affect kernel fissuring (Cnossen *et al*., 2000), while the changes in diffusivities were found to greatly affect drying rates (Cnossen *et al*., 2002). Although tempering helps relax the strains inside a rice kernel which develop during a drying process, tempering temperatures must be kept well above the Tg to preserve the high level of head rice yield (Zhang *et al*., 2003). Single pass drying at a high temperature (80ºC) could be applied without the milling quality deterioration when the kernel was maintained in a rubbery state during the drying and tempering processes (Ondier *et al*., 2012).

Materials and Method

The small-scale dryer used in the experiment was constructed as follows: 115 cm. long and 4.5 cm. wide drying column, 1.5 kW electrical air heater, and 0.66 kW air blower. The air temperatures and flow rates can be continuously adjusted through a control system. The air flow rates were measured with a carefully calibrated thin-plate orifice system at the inlet of the air blower. The average air velocity inside the drying column was evaluated from the mass conservation equation.

The Chainat1 rice variety, one of the most popular varieties in Thailand, was used in this study. The rice was freshly harvested and packed in plastic bags and was then stored in a refrigerator at 5°C; the storage was not a required procedure but was needed for

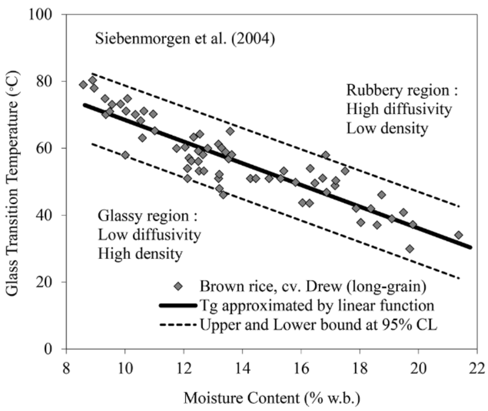

Figure 2. Glass transition temperatures vs. moisture contents for brown rice kernels (cv. Drew) (Seibenmorgen *et al*., 2004)

Table 1. Temperatures, air velocities, and rest periods used in the experiment

Drying air temperature (°C)	Drying air velocities (m s^{-1})	Rest periods (min)
40	1	1
	2	1
	3	1
60	1	0, 1
	2	0, 1
	3	0, 1
100	1	0, 1, 2, 4
	2	0, 1, 2, 4
	3	0, 1, 2, 4
130	1	0, 1, 2, 4
	2	0, 1, 2, 4
	3	0, 1, 2, 4
150	1	0, 1, 2, 4
	2	0, 1, 2, 4
	3	0, 1, 2, 4

logistical reasons. Before an experiment, the bag of rice was exposed and allowed to adjust to ambient conditions for 12 h; after that, the rice straws and weak paddy were removed with a cleaning machine. The cleaned paddy was set in ambient air for another 1 h before going through the experiment. Each experimental run used 3 kg of paddy with moisture nominally at 21%w.b. The wet paddy was poured onto the hopper on top of the drying column after which the shutter at the column top was then opened to let the paddy free-fall while a clock was set. The 3 kg of paddy emptied from the hopper in about 20 s and ended up in the bucket at the bottom of the drying column. The bulk temperature of the paddy pile was then measured, a sample of paddy was collected (for moisture measurement), and the paddy was rested for a determined period of time as required by the experiment. Drying was repeated until the moisture level of the paddy reached about 14%w.b.

The experimental conditions used are indicated in Table 1. At 40°C, the continuous drying experiment was not performed because the temperature level could not be attained due to the heating of the air by friction in the air compressor. Also, at 40 and 60°C the rested drying tests at 2 and 4 min rest periods were not performed due to experimental time limitations.

To measure the moisture of the paddy in the drying process, 15 g of paddy from the samples were collected into sealed plastic bags for every 10 drying cycles through the drying column and allowed to rest in ambient air for 6 h before being measured for moisture by the oven method which dried the paddy at 103°C for 72 h (AACC, 1995).

The primary specific energy consumption (PSEC) is defined as the heat energy used to evaporate 1 unit of water from the drying material. The unit of PSEC is defined as mega joules per kilogram of water evaporated (MJ kg. water. evap^{-1}.). Therefore, a lower PSEC is desirable since it means a saving in energy cost which could be quite significant in the economy of a drying operation. The PSEC was calculated according to these equations:

$$PSEC = \frac{Q}{(w_1 - w_2)} \tag{1}$$

$$Q = \dot{m}_a\left[(1-W_a)c_a + c_v W_a\right]\cdot\left[T_2 - T_1\right]\cdot \Delta t \tag{2}$$

$$\Delta t = \left[t_{\text{drying time 1 cycle}} \times N_{\text{drying pass}}\right] \tag{3}$$

$$w_1 - w_2 = w_1 \frac{(M_1 - M_2)}{(1 - M_2)} \tag{4}$$

For comparison purposes, continuous dryings (without rest) were also conducted wherein 100 g of paddy were put into the drying column and heated airs at set temperatures were blown from underneath the drying column with the absolute velocities of 4.47, 5.20, and 5.93 m s^{-1}. These velocities were computed to be the paddy/air relative velocities resulting from the 1, 2, and 3 m s^{-1} absolute air velocity used in the normal dryer (with rest periods), respectively. The air velocities used were in the fluidization range and the paddy was observed to actually become fluidized in the continuous drying process. At these high relative air velocities during the normal drying (with rest), however, the paddy had no trouble falling down the column because it had an initial downward momentum to begin with and the impact forces from the upstream paddy also helped to push the paddy down through the drying column.

The control experiment was conducted by using a tray drying process. The drying used ambient air at about 30°C and air velocity about 1 m s^{-1}. It required 48 h for the moisture to reduce from 21% to 13% w. b. Since the temperature and air velocity were low, the paddy was expected to be of high quality with low breakage and high whiteness.

To measure breakage and whiteness, 1 kg of paddy that had finished a drying process was prepared by resting in ambient air for a week; this was to allow for a relaxation of the surface stresses that were caused by the unevenness of moisture and temperature distributions during the drying process. Three machines were used in the milling process: a milling machine, polishing machine, and separation machine, all of which were manufactured by Ngec-seng-huad Co. Ltd (Thailand). The head rice yield (HRY) was calculated according to the following relationship (Seibenmorgen, 2013):

$$\%HRY = \frac{\text{head rice weight}}{\text{dried paddy weight}} \times 100 \quad (5)$$

where head rice was defined as the grains that were at least 80% of its full length. The Minolta Corp. (Osaka, Japan) equipment model CR-300 w/DP-301 was used in color measurement by using the L*a*b* standard procedure; the whiteness index, WI, was computed according to,

$$WI = 100 - \sqrt{\left(100 - L^*\right)^2 + a^{*2} + b^{*2}} \quad (6)$$

Results and Discussion

Drying Rate

Figures 3, 4, and 5 show the moisture contents (ordinates)as related to the drying cycles (abscissa) which are directly related to the drying time, at the drying temperatures of 100, 130, and 150°C, respectively. It is observed that all the distributions are nearly linear with different slopes, especially at the early period of the drying curve, as can be seen in grain drying with the spouted bed technique (Madhiyanon and Soponronnarit, 2005). This resulted from the effect of moisture relaxation during the resting periods, i.e., moisture diffused from the inside to the surface of the kernel. This should simplify water vaporization when grain transits to the drying tube, where the grain is exposed to a relatively high temperature and velocity of the drying air. The drying characteristic of the free-fall dryer are

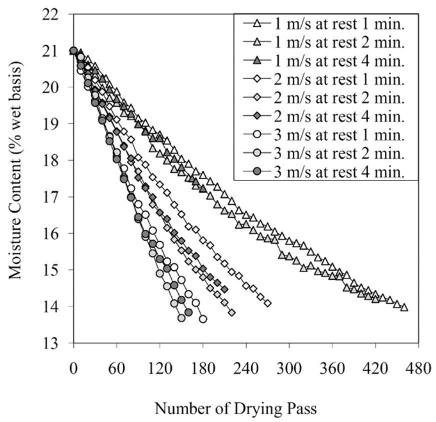

Figure 3. Reduction of paddy moisture content at drying air temperature 100°C

very different from the fluidized bed technique, in which the drying curve shows the exponential decay fashion (Poomsa-ad *et al*., 2002).

The higher air temperatures and the higher air velocities tend to produce progressively faster drying and extend the linear characteristic interval of the drying curves to a lower moisture content level. Longer rest periods in general also help promote faster drying; this is believed to be due to the diffusion of moisture from the kernel's core to the surface during resting (Dong *et al*., 2009). If the rest periods were too long (when compared with the intensity of the drying condition), however, a reduction in the drying rate could result (see the case of the rest period of 4 min at 100ºC in Figure 3). This was possibly due to the kernel temperature dropping below the glass transition temperature, Tg, which was caused by the longer time provided for the heat transfer process during the rest.

At the drying temperatures of 130ºC and 150ºC, the kernel temperature was higher than the Tg for almost all the resting period (data not show); the starch in the kernel was mostly in the rubbery state which results in the same order of magnitude of the effective diffusivity

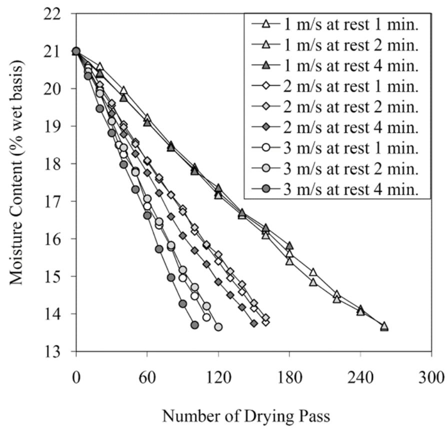

Figure 4. Reduction of paddy moisture content at drying air temperature 130ºC

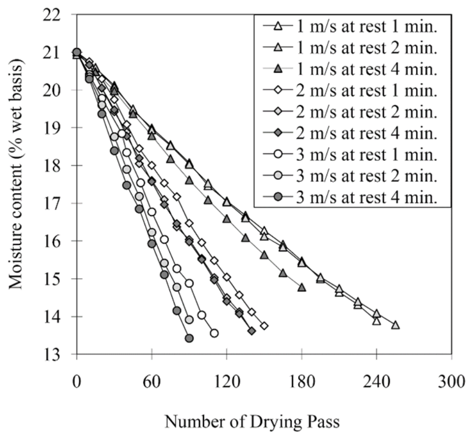

Figure 5. Reduction of paddy moisture content at drying air temperature 150ºC

in these experiments. As a result, the fastest, the medium, and the lowest moisture reductions should be found at the resting periods of 4, 2, and 1 min, respectively, as shown in Figures 4 and 5. However, in Figure 4 the drying curves in the cases of the resting periods of 1 min and 2 min overlapped along the drying curve except at the tail (low moisture content level). This could be possible because the ambient temperature in the case of the resting period of 2 min was lower than that of the resting period of 1 min in all of the resting intervals, e.g. the average ambient temperature in the case of the resting periods of 1 min and 2 min at air speed 2 m s^{-1} were 30.57°C and 27.84°C, respectively. In the case of the resting period of 2 min, during the resting period the grain lost more heat to the environment, with lower bulk paddy temperature, which decreased the moisture migration from the center to the surface of the kernels. Therefore, the similar evaporation rates of moisture in the drying tube between the resting periods of 1 min and 2 min could be achieved. Moreover, this occurrence was found in Figure 5, e.g. at the air speed 2 m s^{-1} the average ambient temperature in the case of the resting period of 2 min was higher than that of the resting period of 4 min (30.61°C and 26.70°C, respectively).

Figure 6 shows the average drying rates for all the air temperatures, air velocities, and rest periods used in the experiment. Basically, this is just a summary of all the drying curves into 1 plot. It is observed that the drying rates increase quite rapidly with the air temperatures and air velocities but relatively less rapidly with the rest periods. At 130°C, the drying rates show drastic bends toward a slower rate. This result could be described by using the glass transition temperature (Tg) concept.

At the beginning of drying, the rice kernels were in the glassy state because their initial temperatures and moisture contents were about 28-30°C and 21%w.b., respectively. During drying, the bulk paddy temperatures were increased rapidly in the first drying period after which they stayed mostly constant. At the 100°C drying air temperature, the bulk paddy temperatures were lower than the Tg which indicated that starch in the kernel was in the glassy state during the drying process. At the 130°C drying air temperature, the bulk paddy temperatures were higher than the Tg in the first drying period as shown in Figure 7 for the drying test at the 1 min. rest period. Therefore, at the 130°C drying air temperature, the starch in the kernel was mostly in the rubbery state during the drying process in which the moisture could thus diffuse out of the rice kernel much faster (Cnossen *et al.*, 2002; Sun *et al.*, 2002) than in the case of the 100°C drying air temperature. The increase of the drying rates in Figure 6 from the 100°C to 130°C drying air temperature were higher

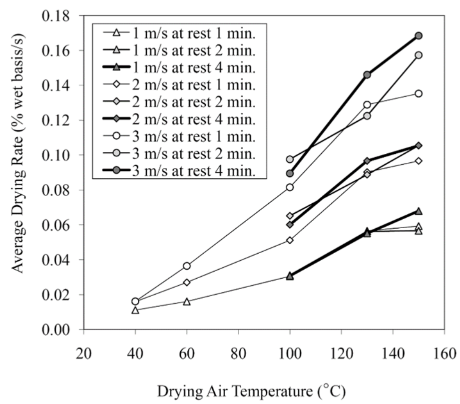

Figure 6. The effect of temperatures, air velocities, and rest periods to the average drying rate

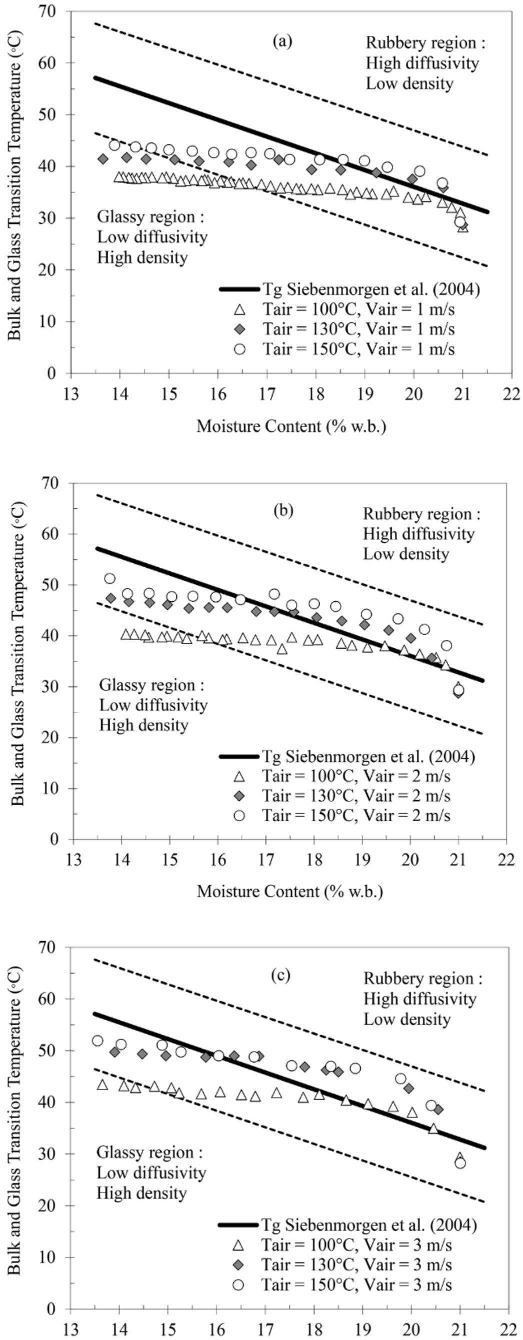

Figure 7. Bulk paddy temperature at rest period of 1 min on state diagram

than between the 130°C to 150°C drying air temperature because of the effect of the material state transition in the rice kernels.

Primary Specific Energy Consumption (PSEC)

The relationship of the PSEC to the air temperatures and air velocities is plotted in Figure 8 for the rest period of 1 min. It is evident that the PSEC increases with the air temperature and/or velocity. This is because the higher air temperature and/or the faster air velocity leaves the drying column with more drying potential leftover than the lower air temperature and/or the slower air velocity, despite the fact that it absorbs more moisture in each drying pass (resulting in a higher drying rate, see Figure 6).

In other words, the PSEC level depends on the ability of the dryer to exchange heat and moisture between the grain and the air. Because of the limitation of the drying tube length (1.15 m) and the short contact time between the grain and the air in the drying tube (0.5 s/drying round) in this study, the grain cannot get the full drying potential of the drying air. Then, the exhaust drying air still has more drying potential (high temperature and low relative humidity), especially under a high air temperature condition. As a result, the minimum PSEC was found at the drying temperature equal to 40°C, because the grain can get a greater percentage of the drying potential from the exhaust drying air than under the other drying temperature conditions. The PSEC reduction was also found at the 130°C drying temperature (not only at 40°C). The curves show strong dips at 130°C, and this result is again believed to be related to the increase of the drying rate because of the glass transition phenomenon in the rice kernels as discussed previously. It is likely that the paddy bulk temperature at this air temperature was at the incipient glass transition temperature (which is approximately at 35-55°C). At this point, the property of the paddy changes abruptly which increases its heat and mass transfer properties. As a result, a significant reduction of drying time was found under this drying temperature condition. This affects the instantaneous reduction of the PSEC at 130°C and 150°C.

The optimal operating point of this study has yet to be found. It should not be a definite point, however, since each drying operation possibly has a different criterion of optimality. For example, one might desire to obtain a lowest possible energy consumption while another could bear a moderate energy consumption but require the shortest drying time possible. Therefore, the optimal operating points of these 2 operating requirements are different. In this specific experiment, the compromised operating point which gives both low energy consumption and time required was found to be at an air temperature of 130°C

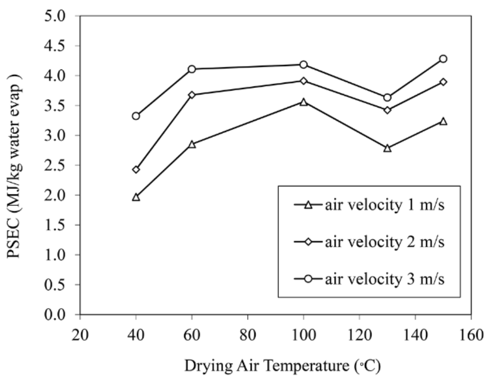

Figure 8. Primary specific energy consumption (PSEC) when using resting period of 1 min

and air velocity of 3 m s^{-1}. Be reminded that a slower air velocity, while being more energy efficient than a faster air velocity, will requires more secondary energy (such as the power required for the air blower and for the paddy conveyor) due to the fact that it must operate over a longer time period.

At the 130ºC drying air temperature, the average PSEC of this dryer is about 3.3 MJ kg.water.$evap^{-1}$ which is already about 2 times better than the fluidized and the spouted bed dryers (Madhiyanon and Soponronnarit, 2005; Sarker *et al*., 2015a). This should significantly help to reduce the thermal energy cost in the dryer operation.

For a commercial-scale dryer which employs a much longer drying column, a faster air velocity could possibly produce a lower PSEC than a slower air velocity since the leaving air's drying potential would be more fully utilized than in this small-scale test.

Head Rice Yields (HRYs)

Before the detailed discussion, it would be useful to consider the effects of the final moisture content of paddy before milling, as presented in Figure 9. The data points for the normal drying technique (with rest) seem to be distributed orderly but are segregated from those of the continuous drying ones (without rest). Among the continuous drying data groups, the low temperature group (60ºC) is segregated from those of the high temperature group (100-150ºC). This proved that continuous, high temperature drying is indeed a major cause of breakage. More HRYs at a higher moisture content are believed to be due to the gelatinization process that occurs in the high-temperature paddy kernel which tends to mend fissures within the kernel, especially at a high moisture content (Madhiyanon and Soponronnarit, 2005; Prachayawarakorn *et al*., 2005a; Chungcharoen *et al*., 2015).

At a low moisture content, however, HRYs are almost zero. For the normal free-fall drying, however, the trend is reversed wherein the HRYs decrease as the final paddy moisture increases. The trend observed here is consistent with the findings of Chitra (1989).

It was also observed that the free-fall dryer produces slightly better HRYs than the control dryer (tray dryer). Admittedly, this research issue was not planned in advance but was rather the ramification of the inability to control the final paddy moisture because its values were measured 6 h after any experiment.

It is obvious from Figure 9 that the HRYs of the present drying technique, even when rested for only 1 min, increase significantly from the level of the continuous drying process. The rest of 1-4 min here is an order of magnitude shorter than the time required in the tempering process, which is often employed in conventional drying techniques. The reason

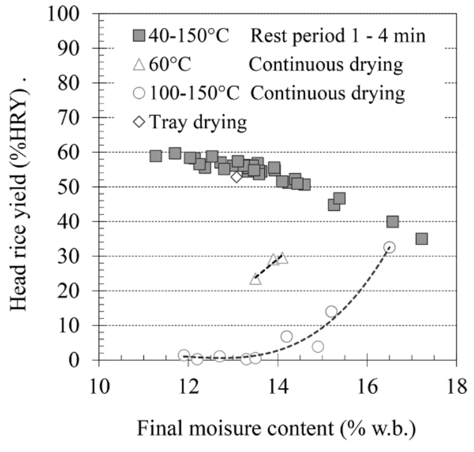

Figure 9. Relationship between head rice yield and final moisture content before milling

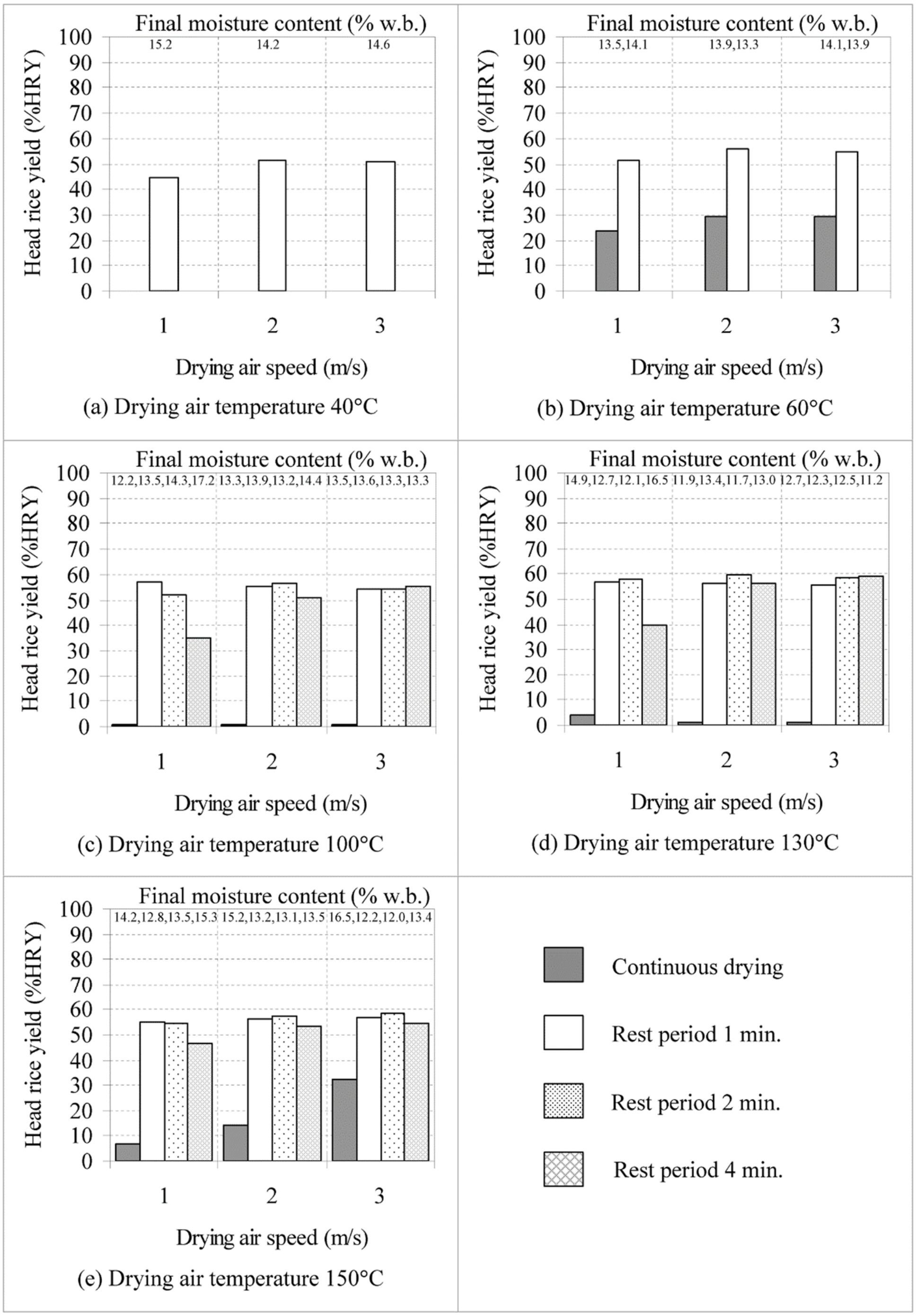

Figure 10. Head rice yield and final moisture content under any drying condition

for this lies perhaps in the fact that the contact time between the paddy and the drying air is very short (of an order of 1 s) which allows the high moisture gradient area to penetrate only to within the kernel's near surface, but not into the kernel' s core. Therefore, a short period of rest is enough to relax the steep moisture gradient in this study. The reduction of the intra-kernel moisture content gradient is effective to reduce the maximum tensile stresses at the center of the rice kernel (Li *et al*., 1999) and then lower the percentage of fissured kernels (Dong *et al*., 2010).

Figure 10 shows the HRYs at various air temperatures, air velocities, and rest periods. Note that the final moisture contents of the paddy before milling are also indicated on top of each graph. Except at 60ºC, the continuous drying (without a rest period) gives almost zero HRYs while the normal dryings give good HRYs except at 100ºC and 130ºC with air velocity of 1 m s^{-1} and a rest period of 4 min (Figure 10(c) and 10(d)). The reason for these low HRYs is the high final paddy moistures at 17.2%w.b. and 16.5%w.b., respectively; due to the limitation of working hours, these experiments was terminated after 12 h. In general, it is evident that the longer rest periods and faster air velocity do not give significantly different HRYs. The prominent cause for the variability in HRY is evidently the final moisture content of the paddy (Chitra, 1989).

Not shown in Figure 10 is the HRY of the control sample (52.82% at 13%w.b.) At about this final paddy moisture level, all of the free-fall dryer results give better HRYs than the control value; some values are as high as 58%. The reason for the increase in the HRY is probably, again, the effect of the rest periods which help alleviate the steep moisture gradient, while the control drying, despite using a slower process, might have some very wet and very dry spots randomly distributed within the paddy bed due to random piling of grains. These wet/dry spots in turn can cause local high moisture gradient spots with the ensuing fissuring.

Figure 10 also shows that, at 12% final paddy moisture and less, HRYs are nominally at 60%, about 7% higher than the control value. It is well known in the milling business in Thailand that an increase of the HRY by a mere 1% means a significant profit gain for the millers. Therefore, a dryer that gives higher HRY while adding little cost to the process is very desirable. It has been demonstrated that the free-fall dryer's rate of drying was constant even in this low moisture regime. This means that it should not cost too much in terms of both time and energy consumption to operate the dryer in this drying regime. The free-fall dryer, therefore, has a potential to be employed to achieve very low paddy moisture in order to gain extra profit for millers. Reducing the moisture to below 12%, however, should not help to increase the HRY further, as indicated in Figure 9.

The experiment showed that paddy must be carried back into the drying chamber for many rounds to obtain the desired final moisture content. In this laboratory scale experiment, hand carrying by bucket was used. On an industrial scale, of course, a mechanical conveyer must be used. This could create some impact on the rice, causing some mechanical damage in a commercial application. However, the rice's mechanical damage could be reduced by using a longer drying column, approximately 5 m. long on an industrial scale, to decrease the number of drying passes. In addition, such damage could be reduced by applying gentler conveyer types such as a belt or pneumatic conveyer instead of bucket and screw conveyers.

Whiteness of Milled Rice

In Figure 11, the whiteness indices (WI) are plotted against the drying temperatures. It is observed that the whiteness indices for the free-fall dryer lie between 65.2-69.6%, while that for the control sample is at 66.8%. This proves that the free-fall dryer, despite using rather high drying temperatures, does not cause discoloring of the milled rice. It is interesting to note that, despite the high drying air temperature, the bulk temperature of paddy was quite low. For instance, the air temperature of 150ºC gave a bulk temperature of only about 50ºC. This was probably the major factor that contributes to the high whiteness of the milled rice. The low kernel temperature, in turn, was caused by the short contact time between the paddy and the drying air. In addition, there is the non-adiabatic rest period to help cool down the paddy pile further until it reaches an equilibrium with the surrounding air. It is noted that the non- enzymatic browning reaction in paddy requires high heat and a long exposure time (Soponronnarit, 1997). This requirement is probably why browning occurred in some of the fluidized bed and spouted bed drying procedures (Madhiyanon and Soponronnarit, 2005; Prachayawarakorn *et al.*, 2005a), where the whiteness indices were clearly below that of the control experiment.

Nomenclature

c_a	specific heat of dry air (J kg^{-1} K^{-1})
c_v	specific heat of vapor (J kg^{-1} K^{-1})
E	primary specific energy consumptions (J kg.water.evap^{-1})
M_1, M_2	initial and final moisture content (decimal wet basis)
$\dot{m}_a$	mass flow rate of drying air (kg s^{-1})
$N_{\text{drying pass}}$	number of drying pass
PSEC	primary specific energy consumptions (MJ kg.water.evap^{-1})
Q	primary energy consumption (J)
T_1	inlet dryer/ambient air temperature (K)
T_2	outlet heater/drying air temperature (K)
Δt	total resident time of paddy in drying tube (s)
$t_{\text{drying time 1 cycle}}$	resident time of paddy in drying tube (s)
W_a	inlet air humidity ratio (g.water. vaporg.dry.air^{-1})
w_1, w_2	initial and final mass of paddy (kg)
HRY	head rice yield (%HRY)
L*	black-white dimension
a*	red-green dimension
b*	yellow-blue dimension
WI	whiteness index (%WI)

Conclusions

The free-fall grain dryer has been invented and investigated for its drying rates and energy consumption. It was found that the drying rate for any drying configuration is quite constant throughout the drying range (about 21% to 14% w.b.) with nearly linear decay behavior and that the primary specific energy consumption is significantly lower than that of conventional dryers.

In addition, it had been shown that rest periods of 1-4 min promote high head rice yields (HRY) in the free-fall paddy dryer. The rest periods can increase the HRY from almost zero for the case of the continuous drying

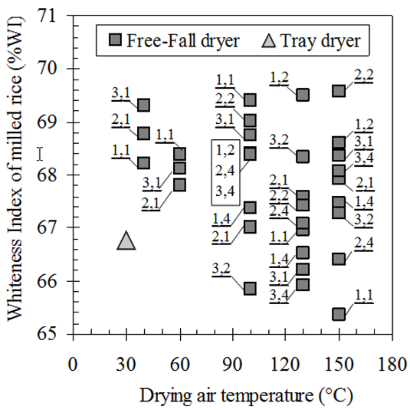

Figure 11. Whiteness index of milled rice under any drying condition

method (rest period at 0 min), to about 55-60% which in some cases even exceeds the level of the control experiment of 52.8%. High HRYs were observed for all the drying air temperatures (60-150°C) used in this study. The whiteness of the milled rice was also good for all the drying temperatures, about the same level as that of the control experiment. The dryer is also easy to build and operate which should make it competitive and can contribute to the drying technology of grains of various kinds such as rice, wheat, corn, and peanuts.

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