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Original Article

Study of drying kinetics and qualities of two parboiled rice varieties: Hot air convection and infrared irradiation

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Abstract

The effect of infrared (IR) and hot air (HA) drying conditions on drying kinetics of Leb Nok Pattani (LNP) rice and Suphanburi 1 (SP 1) parboiled rice and their qualities was studied. Initial moisture content for LNP and SP 1 rice was 54±1 and 49±1% dry-basis, respectively. Drying temperatures of 60-100°C, IR power of 1.0 and 1.5 kW and hot air flow rate of 1.0±0.2 m/s were used for experiments. The results show that HA and IR parboiled rice drying can maintain high head rice yield (HRY) and IR drying with 1.5 kW provided the highest HRY value. Additionally, the qualities analysis showed that whiteness, water absorption, cooking time and pasting property were significantly different compared to reference samples. The specific energy consumption of parboiled rice drying with IR of 1.0 kW at 100°C delivered a low value. Thus IR drying for parboiled rice should promote.

Keywords: energy consumption, head rice yield, medium and long-grain rice, physicochemical quality

1. Introduction

Rough rice or paddy that is subjected to hydrothermal treatment prior to milling is defined as parboiled rice. Parboiling is practiced in many parts of the world such as Asia, Europe, and America (Pillaiyar, 1981; Juliano, 1985). Traditional parboiling involves soaking the paddy in water, followed by steaming and drying (Bhattacharya, 2004). In the ASEAN countries the use of brown rice and parboiled rice product is increasing, especially in health food and green organic products. Paddy after dehusking as so-called brown rice mainly contains more nutritional components (such as dietary fibers, phytic acid, mineral, vitamin E, vitamin B, and γ-aminobutyric acid (GABA) than the milled rice (Kayahara, 2004). The biofunctional components exist mainly in the germ and bran layers, most of which are removed by polishing or milling (Champagne *et al*., 2004). On the other hand side, brown rice takes a longer cooking period and it is somewhat harder to chew than milled rice. Additionally, a brown rice easily deteriorates and develops a smell due to its free fatty acid during storage (Juliano, 1985). Parboiled rice is different from brown rice even if it is a high nutrient like as brown rice. Normally, parboiled rice has lower nutrient loss after milling and cooking because during parboiling process the grain kernel changes its physical properties such as starch which gelatinizes and leads to a high milling yield (Rao and Juliano, 1970; Wu *et al*., 2002). In addition, some essential matter in germs and bran layers mineral penetrate and transfer into starch granules (Tirawanichakul *et al*., 2004a).

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Due to the long period of the rainy season in the Southern part of Thailand, losses during post-harvesting and paddy degradation are relatively high because the fresh paddy has to be harvested in a high relative humidity environment and there is high moisture content which leads to the risk of deterioration (Tirawanichakul *et al.*, 2004b). To strive for added value to the product, rice parboiling process is thus of interest because parboiling reduces some losses and enhances the quality of rice. In Thailand, there are more than 5,900 varieties of rice among which Khao Dawk Mali 105 rice is the most famous and acceptable variety throughout the world for its quality of flavor and texture (Banchuen *et al.*, 2009). However, some non-glutinous rice varieties in the South of Thailand have received little research, especially with respect to value added of the product. Leb Nok Pattani (LNP) paddy, which is a local medium-grain kernel cultivar with large portion of grains, is widely produced in Southern Thailand. LNP rice has a low amylose content and thin kernel so it is easily broken (low head rice yield) and yields a high amount of white belly kernel. Moreover, there are few reports on local rice parboiling including the above variety. In previous research on moisture dehydration for rice varieties, Champagne (1994) reported the heat treatment process for moisture removal of rice and stated that this heat treatment could deactivate lipase and could also slow down the rate of lipid oxidation (Champagne 1994; Houston and Kohler, 1970). Drying, which is one kind of heat treatment, is the most essential stage for producing parboiled rice before storage or packaging. This is because the high moisture content of soaked rice (>35% dry-basis) leads to easy degradation due to many effects such as infection by microorganisms, yellowing by non-enzymatic reaction etc. The drying process is an important process affecting product quality and there are many methods to reduce moisture content such as hot air drying (HA), infrared drying (IR) (Delwiche *et al.*, 1996; Das *et al.*, 2003; Laohavanich and Wongpichet, 2008), and microwave drying (MW) (Therdthai and Zhou, 2009). The appropriate moisture content of grain kernel for long shelf life is about 16±1.0% dry-basis (Soponronnarit, 1997; Tirawanichakul *et al.*, 2004b; Soponronnarit *et al.*, 2005). One of the high efficient methods of heat and mass transfer is electromagnetic irradiation, for example: microwave, infrared and radio frequency. Infrared irradiation technique is easy to set up, has low technical structure, has low construction cost and is an effective method which provides high heat and mass transfer rates, although it affects the color of the product (Ratti and Mujumdar, 1995; Afzal and Abe, 2000; Mongpraneet *et al.*, 2002; Kian and Siaw, 2005). Employing the IR drying method has been known to substantially reduce the drying time and could lower the degradation of bioproduct quality (Sandu, 1986; Ratti and Mujumdar, 1995; Paakkonen *et al.*, 1999; Umesh Hebbar and Rastogi, 2001; Mongpraneet *et al.*, 2002; Kian and Siaw, 2005). Meeso *et al.* (2004) reported the influence of IR drying on paddy moisture reduction and milling quality after fluidized bed drying (FBD). The results showed that combined drying of paddy with IR and FBD technique could maintain the physical quality of rice grain kernels and reduce the specific energy consumption compared to hot air drying. However, the physicochemical, chemical and sensory evaluation for local Thai paddy varieties using infrared and hot air drying were not reported in those previous works.

The objectives of this research were to investigate and compare the effects of two drying sources; hot air convection (HA) and infrared (IR) radiation, for medium-grain parboiled Leb Nok Pattani and long-grain Suphanburi 1 paddy on drying kinetics and physical qualities. The effective diffusion coefficient was evaluated and qualities in terms of head rice yield (HRY), whiteness (W), cooking time, water absorption and pasting property were determined. Finally, specific energy consumption (SEC) was compared in the two drying conditions.

2. Materials and Methods

2.1 Materials

The local medium-grain Leb Nok Pattani paddy (LNP) and long-grain Suphanburi 1 (SP 1) paddy varieties were provided by the Rice Research Institute in Patthalung province, Thailand. Normally, the local rice varieties of Leb Nok Pattani and Suphanburi 1 contain amylose content of 23-25% and 25-27%, respectively (Tirawanichakul, 2004; Tasara, 2008; Bualuang *et al.*, 2011). Due to well-mixing and getting uniform moisture content kernels, the fresh paddy varieties were put in each container (20 kg) and kept in a refrigerator at 4-8°C for 3-4 days. Before testing, the paddy in container was taken out the refrigerator and placed in ambient conditions until grain temperature was the same as surrounding temperature.

2.2 Experimental procedure

The medium-grain LNP paddy was cleaned and soaked in warm water at 70±1°C for 3 h in order to obtain saturated paddy kernels while the long-grain SP1 paddy was soaked at 70±1°C for 4 h. The soaked paddy varieties were then tempered at room temperature for 24 h before steaming at temperature of 100±2°C for 30 min (Arai *et al.*, 1975). These soaking temperature, tempering time and steaming duration of operation were the optimal conditions for parboiled rice without white belly evidence. This parboiling procedure of soaking, steaming and tempering could provide rice kernels partially gelatinized (Cnossen *et al.*, 2000; Cnossen *et al.*, 2003; Taechapairoj *et al.*, 2003; Bhattacharya, 2004; Rordprapat *et al.*, 2005; Bualuang *et al.*, 2011) and then drying with appropriate temperature and drying time could make the starch inside grain kernels fully gelatinized (Kimura *et al.*, 1995; Taechapairoj *et al.*, 2003). In the present study, the parboiled paddy was tray-dried with HA convection and IR radiation using a tray-drying system (PSU-TRD-08-2) which was composed of 1×10 kW electrical heater units and electric

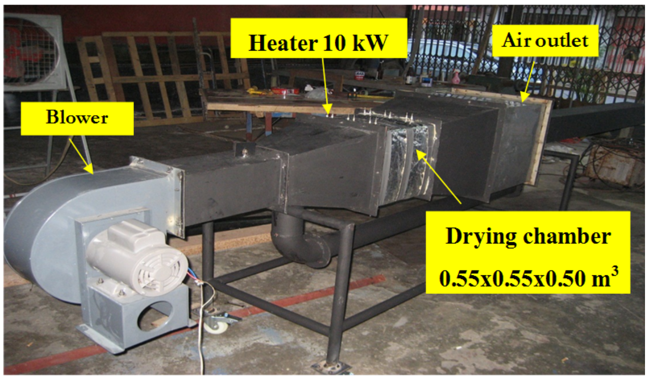


Figure 1. Illustration of tray drying system (PSU-TRD-08 2)

infrared rod, a centrifugal fan driven by a 1.5 hp motor and a temperature controlling unit as illustrated in Figure 1. The drying temperature was controlled by a PID controller with an accuracy of ±1°C while wet bulb temperature, dry bulb temperature, rice grain kernel temperature and drying temperature were measured by K-type thermocouple connected to the data logger (Wisco, Thailand). The experiments were carried out under the condition of drying temperature ranging of 60 to 100°C, inlet air flow rate of 1.0±0.2 m/s, IR power of 1,000 and 1,500 W. In each experiment, the 2 kg samples of parboiled rice were weighed and put on a perforated tray in the drying chamber. The average initial moisture content of the rice sample was in the range of 54±1 and 49±1% dry-basis for LNP and SP 1, respectively. During the drying process the evolution of sample weight was recorded at every 3 min intervals. The sample was dried until the desired final moisture content reached to 22±1% dry-basis. The paddy sample was then taken off the drying chamber and ventilated by aeration until the safe moisture content of dried parboiled paddy was about 14-16% dry-basis for prolonging shelf-life (Soponronnarit, 1997; Tirawanichakul *et al.*, 2004a). Due to relaxed stress inside grain kernels, the samples were then kept in plastic bags for two week before quality evaluation.

2.3 Rice quality

1) Head rice yield (HRY)

Determination of the head rice yield (HRY) was performed according to the procedure set by the Rice Research Institute, Phatthalung province, Thailand. HRY is calculated by dividing the head rice weight by the initial rough rice weight. This value was determined in triplicate.

2) Whiteness of parboiled rice

The whiteness of milled rice samples was measured with a commercial whiteness meter (Model C-300, Kett Electronic Co. Ltd., Japan). This meter measures the whiteness (W) of rice kernels in the linear range of 0 to 100, where 0 corresponds to perfect black surface and the 100 corresponds to the whiteness of magnesium oxide fumes. Before testing, the equipment was calibrated with the provided ceramic plate having a whiteness value of 86.3.

3) Cooking time

Cooking time is the time duration to partial starch gelatinization over 90% of the total starch kernels based on visual observation. Ten grams of mature rice kernels were boiled in 250 ml of distilled water. After 20 min of cooking (Tungtrakul, 1997; Tirawanichakul, 2004), the 10 grain kernels were removed from the water and placed over a Petri dish and grain kernels were then compressed with a spatula in order to visualize and count the grain kernels which had no area of the opaque core inside (fully gelatinized kernels). The same procedure was repeated every minute until all the 10 grain kernels reached to complete gelatinization for two successive cooking times.

4) Water absorption

To determine water absorption, two grams of milled parboiled rice samples were added to 20 ml of distilled water previously heated at 95°C in a test tube covered with cotton plug and placed in a covered thermostatically controlled water bath. The rice samples were cooked according the cooking time in a water bath as previously determined, cooled in water, drained, and placed upside down for 1 h and weighed. The increase in weight was calculated and reported as gram of water absorbed by one gram of rice sample (Juliano, 1985).

5) Pasting property

Pasting properties of parboiled rice flour samples were determined by using a Rapid Visco Analyzer, RVA (Newport Scientific, Model RVA-4, Australia) and the approved method of AACC (1995). Precise rice flour weight of 3.0 g with 14% dry-basis was poured into distilled water (25.0 ml) in a RVA aluminum canister and was mixed thoroughly (total weight of slurry be 28.0 g). The mixture was stirred at 960 rpm for 10 s and then changed to 160 rpm. At the beginning stage, its temperature was first maintained at 50°C for 1.5 min and then the operating temperature was raised to 95°C at a fixed rate of 12°C/min. After that the temperature was maintained at 95°C for 2.1 min, followed by a cooling down to 50°C at 12°C/min and was maintained at 50°C for 2.1 min. These running tests were done in duplicate. The RVA parameters measured were peak viscosity (PV means the maximum hot paste viscosity), holding strength (the trough at the minimum hot paste viscosity), final viscosity (FV means the viscosity at the end of the test after cooling to 50°C), setback viscosity (SBV means the final viscosity minus peak viscosity), peak time (minutes) and pasting temperature (P_{temp} in °C). These RVA parameters were expressed in Rapid Visco Unit (1 RVU = 10^{-2} cP). An

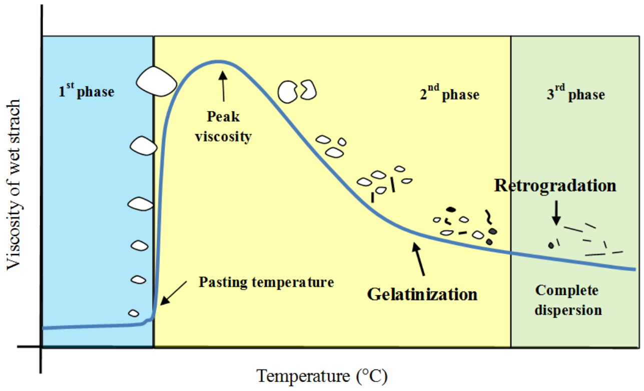


Figure 2. Illustration of viscosity property using rapid visco analyzer (RVA)
[Adapted from Klanarong and Karlkule, 2003]

example of a viscosity curve is illustrated in Figure 2.

To understand the pasting viscosity mentioned above, the explanation is presented as follows. The first point at which the viscosity increases to 1 RVU/s or higher is defined as the onset gelatinization temperature of the rice flour, which means the starting up temperature for heat absorption from heating source of RVA (Tungtrakul, 1997; Bhattacharya, 2004), while the temperature at the peak viscosity (P_{temp}) means the pasting temperature at the top of viscosity curve (Bhattacharya, 2004; Tirawanichakul, 2004). This PV value indicates the water-biding capacity of the mixture. It is often correlated with the final product quality, and also provides an indication of the viscous load likely to be encountered by cooking. Breakdown viscosity means the susceptibility of the starch paste to disintegrate (Mazurs *et al*., 1957) The BV value implies the degree of disintegration of the granules or paste stability. A lower breakdown viscosity of parboiled rice indicates the restricted swelling of starch granules. This indicates states that the cross-bonding of starch molecules inhibiting swelling of starch granules prevented the increase in viscosity and, thus lowered the tendency to disintegrate. Therefore, parboiling rice enhances the stability of the hot starch paste. Setback viscosity is a measure of gelling or retrogradation tendency of rice starch (Dengete, 1984).

2.4 Drying rate and specific energy consumption (SEC)

The average drying rate is defined as amount of moisture transfer during drying time divided by total drying time interval. The following equation was formulated as shown in Eq. (1)

$$\text{Drying rate} = \frac{(M_{in} - M_f)W_d}{\text{Drying time}} \qquad (1)$$

where M_{in} and M_f are initial and final moisture content, in % dry-basis, respectively. W_d is dry weight of sample, in kg, and drying time is total drying time, in hours.

Specific energy consumption (SEC) was defined as the energy required for removing a unit mass of water in drying the parboiled rice from its initial moisture content to the final moisture content. The specific energy consumption was calculated as follows,

$$SEC = \frac{3.6P}{(M_{in} - M_f)W_d} \qquad (2)$$

where P is total amount of energy consumed during drying process, in kW-h, M_{in} is initial moisture content, in % dry-basis, M_f is final moisture content, in % dry-basis, W_d is dry weight, in gram.

2.5 Statistical analysis

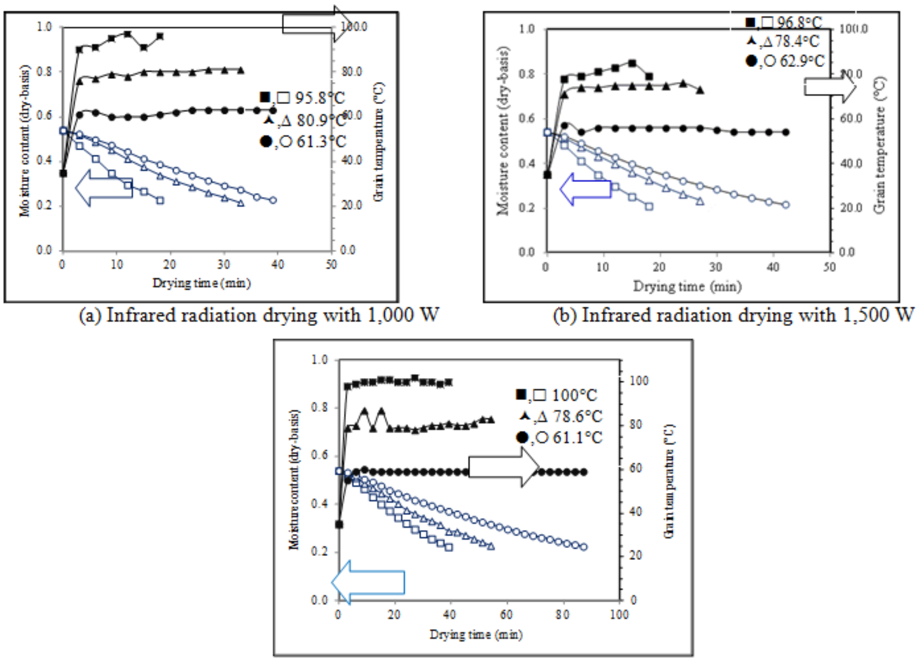
To determine the relationship of drying condition, drying temperature, IR power and all experimental results of qualities, the analysis of variance (ANOVA) was performed in a completely randomized design, using Duncan's Multiple Range Test (DMRT). All determinations of experimental results were done at least in triplicate and all results were evaluated by mean at the confidence limits set up of 95% ($p<0.05$).

3. Results and Discussion

3.1 Moisture content and grain temperature during drying

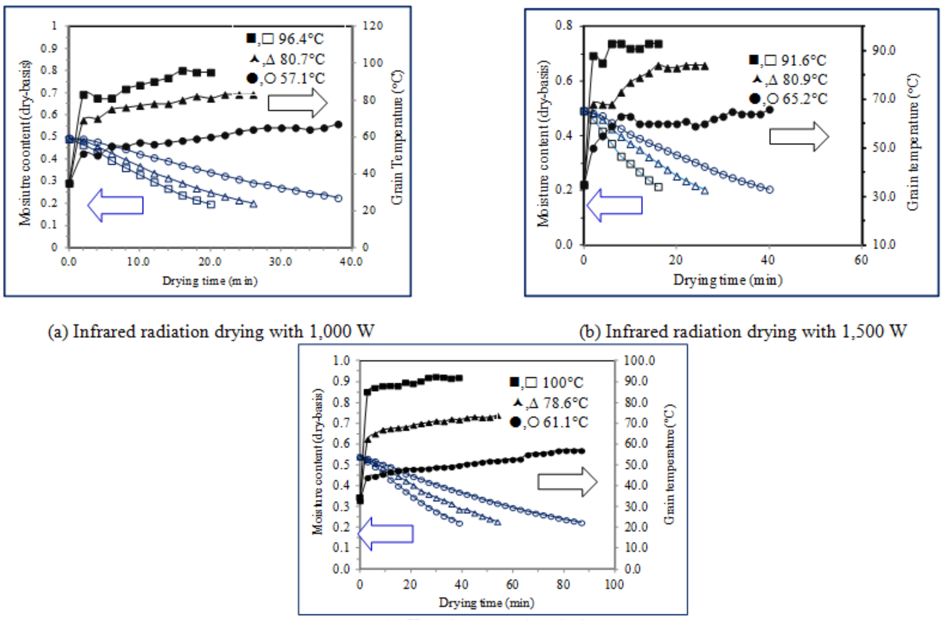
For all experiments, the actual final moisture content of parboiled rice drying was about 21.6±1.4% dry-basis and then the parboiled rice samples were air ventilated by ambient air temperature until the moisture content reached to 14-16% dry-basis. The drying curves of parboiled paddy against drying time are illustrated in Figures 3 and 4. The drying was operated by inlet drying air temperature ranges of 60-100°C for IR and HA heat sources with 1,000 and 1,500 W, respectively and inlet air flow rate of 1.0±0.2 m/s. However, the setting up of inlet drying temperature of 60-100°C was slightly different from the average measured temperature during run experiments because the measured temperature was determined by means of 3 measured data inside the drying chamber. The drying rate of both parboiled rice varieties which were determined by Eq. (1) was identified as a falling drying rate period because at the beginning of the drying period the moisture transfer was not constant. The evolution of moisture transfer for both parboiled LNP and SP 1 rice was dependent on drying temperature and was an exponential function of drying time. In addition, the results of Figures 3 and 4 show that the rate of moisture transfer increased with increasing of drying temperatures and the drying rate seemed to be independent of the rice variety. The average drying rate at high temperature was relative high compared to that at low temperature.

Considering the different heat sources for drying parboiled rice, as shown in Table 1, the average drying rate of both parboiled rice varieties with IR power of 1,500 W was



(a) Infrared radiation drying with 1,000 W
(b) Infrared radiation drying with 1,500 W
(c) Hot air convection drying

Figure 3. Moisture content and grain temperature against drying time of Leb Nok Pattani (LNP) parboiled rice drying with (a) IR 1,000 W, (b) IR 1,500 W and (c) hot air among inlet drying temperatures of 61.1-100°C



(a) Infrared radiation drying with 1,000 W
(b) Infrared radiation drying with 1,500 W
(c) Hot air convection drying

Figure 4. Moisture content and grain temperature against drying time of Suphanburi 1 (SP 1) parboiled rice drying with (a) IR 1,000 W (b) IR 1,500 W and (c) hot air among inlet drying temperatures of 57.1-100°C

relatively high compared to drying using IR power of 1,000 W and HA drying, respectively. This is because energy in the form of electromagnetic wave (IR) can be transferred and thus the energy absorbed directly to the rice grain kernel by heat radiation with a low heat loss to the surrounding. The drying curves of LNP and SP 1 rice drying with IR, which is illustrated in Figures 3(a)-(b) and Figures 4(a)–(b), showed a rapid decrease compared to HA drying results shown in Figures 3(c) and 4(c), respectively. Additionally, the grain kernel temperature of both rice varieties reached to the dry-

Table 1. Whiteness and head rice yield of dried parboiled rice using different heat sources of two rice varieties with drying temperatures of 60-100°C

Leb Nok Pattani (LNP)						Suphanburi 1 (SP 1)					
Drying temperature (°C)	Drying time (min)	Drying rate (kg/h)	M_{in} (M_f)* (% dry-basis)	HRY (%)	W	Drying Temperature (°C)	Drying time (min)	Drying Rate (kg/h)	M_{in} (M_f)* (% dry-basis)	HRY (%)	W
Hot air (HA) drying						Hot air (HA) drying					
Raw rice (reference)	-	-	16.0(16.0)	50.0[d]	12.3[d]	Raw rice (reference)	-	-	16.0(16.0)	58.2[d]	37.9[a]
Control rice	-	-	55.7(16.1)	63.6[a]	18.7[b]	Control rice	-	-	50.1(16.8)	71.8[b]	16.3[c]
61.1	87	0.07	54.0(22.0)	69.2[b]	18.2[c]	61.3	89	0.06	48.9(20.2)	71.1[c]	16.7[b]
78.6	54	0.11	54.0(23.0)	63.7[c]	18.8[b]	80.1	51	0.13	49.5(20.1)	71.8[b]	16.3[c]
100	39	0.16	54.0(22.1)	66.7[b]	19.8[a]	96.2	37	0.16	49.3(20.3)	72.1[a]	16.2[c]
Infrared (IR) drying of 1,000 W						Infrared (IR) drying of 1,000 W					
Raw rice (reference)	-	-	16.0(16.0)	50.0[d]	12.3[c]	Raw rice (reference)	-	-	16.0(16.0)	58.2[d]	37.9[a]
Control rice	-	-	55.7(16.1)	63.6[a]	18.7[b]	Control rice	-	-	50.1(16.8)	71.8[b]	16.3[c]
61.3	54	0.11	54.0(23.7)	67.5[b]	19.2[a]	57.1	38	0.14	50.2(20.8)	70.7[c]	15.6[d]
80.9	30	0.21	54.0(23.1)	67.3[b]	19.6[a]	80.7	26	0.23	48.7(20.0)	72.6[a]	16.9[b]
95.8	24	0.26	54.0(22.5)	67.2[b]	19.2[a]	96.4	20	0.30	49.7(20.2)	71.2[b]	16.3[c]
Infrared (IR) drying of 1,500 W						Infrared (IR) drying of 1,500 W					
Raw rice (reference)	-	-	16.0(16.0)	50.0[c]	12.3[c]	Raw rice (reference)	-	-	16.0(16.0)	58.2[e]	37.9[a]
Control rice	-	-	55.7(16.1)	63.6[a]	18.7[b]	Control rice	-	-	50.1(16.8)	71.8[c]	16.3[c]
62.9	43	0.12	54.0(23.1)	69.5[b]	18.9[b]	65.2	40	0.15	48.7(20.4)	72.5[a]	16.8[b]
78.4	27	0.24	54.0(23.1)	69.3[c]	18.8[b]	80.9	26	0.23	49.3(20.1)	72.3[b]	16.8[b]
96.8	18	0.30	54.0(23.1)	70.6[b]	19.5[a]	91.6	16	0.35	49.2(20.8)	72.9[a]	16.5[c]

Note: * M_{in} (M_f) is initial moisture content (final moisture content) in % dry-basis.
The different letters within the same column show data has significant difference at confident percentage of 95% ($p<0.05$).
Control rice is parboiled rice sample which is dried by ambient air ventilation. And raw rice or reference rice sample is fresh paddy which is dried by ambient air ventilation

ing temperature with small different time (less than 15 min) implying the high efficient heat transfer of the thin-layer tray drying as shown in Figures 3 and 4. This evolution of moisture transfer of rice drying time using IR radiation has a lower energy consumption than HA drying correlated to low drying time. This leads to considerable energy saving, as discussed in the section 3.3.

3.2 Rice quality

1) Head rice yield (HRY)

The relationship between HRY value and drying temperature is presented in Table 1. The head rice yield for LNP and SP 1 parboiled rice with initial moisture content of 54±1 and 49±1% dry-basis, respectively, and drying temperature was set up ranging between 60 and 100°C. As shown in Table 1, the HRY value of both parboiled rice varieties was higher than that of the reference rice sample (fresh rice dried with ambient air ventilation) and control rice sample (parboiled rice dried with ambient air ventilation). This is because soaking, tempering and drying render starch inside rice grain kernels to fully gelatinization. This phenomenon agrees well with the results of previous works (Rao and Juliano, 1970; Inprasit and Noomhorm, 2001; Taechapairoj *et al.,* 2003; Rordprapat *et al*., 2005; Soponronnarit *et al.,* 2005). The results of Table 1 show that the HRY value of LNP parboiled rice which was dried by drying temperature ranges of 60-100°C was not much different and drying with IR power of 1,500 W got the highest HRY value. This is because high infrared power can penetrate more deeply and the heat radiation can transfer into the rice grain kernel leading is greater starch gelatinization. In the same trend as medium-grain LNP rice variety, the HRY of long-grain SP 1 parboiled rice was relatively high when drying temperature increased. The increasing change of head rice yield obtained from the both parboiled paddy dried at higher temperature is different from drying with a lower temperatures, that is, the head rice yield is relatively improved and higher in particular at the initial moisture content of over 32.5% dry-basis (Cnossen *et al*., 2003; Tirawanichakul *et al*., 2004a; Rodpprapat *et al.*, 2005; Soponronnarit *et al*., 2008). Due to swelling effect, the larger amount of HRY for the high-temperature treated sample virtually denotes the stronger intra-granular binding forces, making the kernel resistant to abrasive forces during the milling process (Adhikaritanayake and Noomhorm, 1998). The improvement of binding forces amongst granules is caused by their swelling together with leaching of amylose. The swollen granules are gelatinized, but the gelatinization that occurred partially formed since the water content inside kernel in this study is not enough to form the complete gel (Swinkels, 1985; Seibenmorgen and Perdon, 1999; Cnossen *et al.*, 2000; Cnossen *et al.*, 2003). This evidence corresponds to some previous works which can be used to explain the pasting property of rice flour (Juliano, 1985; Chen, 1990; Nakateke and Noomhorm, 2001; Cnossen *et al.*, 2003; Tirawanichakul *et al.*, 2004a; Therdthai and Zhou, 2009). In the present study, significant differences in head yield of parboiled rice were found for the various drying combinations, especially on IR drying. Additionally, the head rice yield of dried parboiled rice using IR and HA technique was increased over 20% compared to the reference rice samples. These results correspond to the previous reports (Cnossen *et al.*, 2003; Rodprapat *et al.*, 2005; Soponronnarit *et al.*, 2008).

2) Whiteness

The whiteness (W) of dried parboiled rice at temperature of 60-100°C was determined as presented in Table 1. The results showed that the whiteness of both dried parboiled rice varieties was significantly different from the reference rice and control rice samples among average drying temperatures of 61.1-100°C. The whiteness value slightly fluctuated with drying temperature. The whiteness value varied in ranges of 18.2-19.8 and of 15.6-16.9 for LNP and SP 1 rice variety, respectively. The change in whiteness for parboiled SP 1 rice was not very sensitive to drying temperature compared to parboiling process (soaking, steaming, tempering and drying). The reference SP 1 rice sample was milled rice and the control SP 1 rice sample was soaked paddy and dried by ambient air ventilation. So the whiteness value of the reference sample is quite high because of no effect of parboiling process corresponding to the previous work (Tirawanichakul *et al.*, 2004a; Rordprapat *et al.*, 2005). The control SP 1 rice sample was soaked rice so its whiteness value was quite low brightness similar to the parboiled SP 1 rice samples in each experiment which were soaked paddy before drying with temperatures of 60-100°C. The effect of whiteness was caused by diffusion of color of rice hull to starch inside the grain kernel (Rordprapat *et al.*, 2005) and parboiling process such as drying temperature over 40°C (Soponronnarit *et al.*, 1998; Nakateke and Noomhorm, 2001; Inprasit and Noomhoom, 2001; Tirawanichakul, 2004). To compare with the LNP rice sample, the greater amylose content of SP 1 is, so the more yellowing is. The yellowing implies the low brightness of the rice kernel sample (Soponronnarit *et al.*, 1998; Tirawanichakul *et al.*, 2004a; Tirawanichakul *et al.*, 2004b). Additionally, the yellowing of biomaterial can be explained by the effects of the Maillard non-enzymatic browning reaction, especially on high temperature processes (Gras *et al.,* 1989; Bhattacharya, 2004; Soponronnarit *et al.*, 1998; Inprasit and Noomhorm, 2001; Tirawanichakul *et al.*, 2004a; Tirawanichakul *et al.*, 2004b) such as soaking (Kimura *et al.*, 1976; Islam *et al.*, 2002; Bhattacharya, 2004), steaming, tempering, drying (Cnossen *et* al., 2003; Islam *et al.*, 2002; Taechapairoj *et al.,* 2003; Rodprapat *et al.*, 2005) and storage (Soponronnarit *et al.*, 1998; Tirawanichakul, *et al.*, 2004b). However, the physical quality of parboiled rice for customer prefers parboiled rice varieties on their yellowing and low white belly (Rodprapat *et al.*, 2005). The Maillard reaction involves carbonyl groups of reducing sugars and amino groups of amino acids (mainly lysine), peptides, or proteins and induces nutritional changes. Apart from their reactions with amino groups, carbohydrates can also undergo isomerisation and degradation reactions (Villamiel *et al.*, 2006). Moreover, the rice bran or rice hull pigments can affect parboiled rice color since they leach out during soaking in excess water and diffuse into the endosperm during steaming (Lamberts *et al.*, 2006).

The whiteness and head rice yield of parboiled rice drying in this work corresponds to other works which reported the effect of steaming and temperature on the lightness of parboiled rice (Jayanarayan, 1965; Bhattacharya and Rao, 1966; Kimura *et al.*, 1993; Cnossen *et* al., 2003).

As shown in Table 1, the whiteness value of both reference rice samples showed that the whiteness of LNP parboiled rice is slightly lower luminous than SP 1 parboiled rice. This may be because medium-grain LNP rice variety is thinner and shorter than the long-grain SP 1 rice variety so the LNP rice had low reflectance correlated with low brightness compared to SP 1 rice samples. There are not references related to the effect of grain size on color of rice. However, the whiteness value of control rice and parboiled LNP and SP 1 rice samples with drying temperatures of 60-100°C showed the same trend. The advantage of this work is the demonstration of how to enhance high physical quality for local parboiled rice in terms of head yield and parboiled rice yellowing and how to reduce loss in the post-harvesting period.

Thus, in present study HA and IR drying at high drying temperature over 60°C and rice parboiling process for medium-grain LNP and long-grain SP 1 rice varieties and more pronounced on the significant changes in whiteness and yellowness than some other research works (Gras *et al.,* 1989; Tirawanichakul *et al.*, 2004a; Rordprapat *et al.*, 2005; Donludee *et al.*, 2009) and some other drying techniques (Sandu, 1986; Taechapairoj *et al.*, 2003; Cao *et al.*, 2004; Tirawanichakul *et al.*, 2004a; Soponronnarit *et al.*, 2005; Tirawanichakul *et al.*, 2007)

3) Water absorption and cooking time

Table 2 illustrates the water absorption property of LNP and SP 1 parboiled rice compared to the control and reference rice samples. The results show that the water absorption of medium-grain LNP and long-grain SP 1 parboiled rice varieties was lower than that of the reference rice sample. This is because the parboiling process can enhance rice aging and also enhance the hardness value of rice (Bhattacharya

Table 2. Water absorption and cooking time of both rice varieties

Leb Nok Pattani (LNP)			Suphanburi 1 (SP 1)		
Drying temperature (°C)	WaterAbsorption (±0.02)	Cooking time (min)	Drying temperature (°C)	Water absorption (±0.02)	Cooking time (min)
Hot air (HA) drying			Hot air (HA) drying		
Raw rice (reference)	3.64[a]	42[b]	Raw rice (reference)	3.55[a]	48[d]
Control rice	2.80[d]	54[a]	Control rice	2.39[c]	54[a]
61.1	3.37[b]	50[a]	61.3	2.45[b]	52[c]
78.6	3.22[c]	52[a]	80.1	2.32[c]	54[a]
100	3.12[c]	52[a]	96.2	2.31[c]	53[b]
Infrared (IR) drying of 1,000 W			Infrared (IR) drying of 1,000 W		
Raw rice (reference)	3.64[a]	42[d]	Raw rice (reference)	3.55[a]	48[c]
Control rice	2.80[c]	54[c]	Control rice	2.39[b]	54[a]
61.3	3.30[b]	58[c]	57.1	2.41[b]	53[b]
80.9	3.34[b]	68[b]	80.7	2.42[b]	56[a]
95.8	3.24[c]	76[a]	96.4	2.18[c]	56[a]
Infrared (IR) drying of 1,500 W			Infrared (IR) drying of 1,500 W		
Raw rice (reference)	3.64[a]	42[d]	Raw rice (reference)	3.55[a]	48[c]
Control rice	2.80[d]	54[c]	Control rice	2.39[b]	54[b]
62.9	2.90[b]	58[c]	65.2	2.35[b]	54[b]
78.4	2.79[c]	65[b]	80.9	2.31[c]	57[a]
96.8	2.74[c]	64[b]	91.6	2.31[c]	58[a]

Note: The different letters within the same column show data has significant difference at confident percentage of 95% ($p<0.05$).
Control rice is parboiled rice which is dried by ambient air ventilation.
Raw rice or reference rice is fresh rice which is dried by ambient air ventilation

and Rao, 1966; Cnossen *et al*., 2000; Tirawanichakul, 2004; Rodprapat *et al*., 2005). The water adsorption and swelling capacity of parboiled rice after cooking increased and became similar to those properties of rice which was stored for 3–6 months, i.e., so-called conventionally aged rice (Gujaral and Kumar, 2003). The water absorption is relatively low when rice drying using drying temperatures of 60-100°C while the cooking time for both LNP and SP 1 parboiled rice and control rice samples was high compared to the reference rice sample. These phenomena lead to a long period of cooking which is correlated to the results in Table 2. This evidence implies their gelatinization during parboiling process affected the cooking time corresponding to medium-grain and long-grain rice varieties (Rordprapat *et al.*, 2005; Soponronnarit *et al.*, 2005; Soponronnarit *et al*., 2008).

4) Pasting property

Table 3 shows the pasting property of two parboiled rice varieties in the case of HA and IR drying. Viscosity of parboiled rice flour determined by RVA representing the viscosity of starch during heating cycle follows in the same pattern as Figure 2. On the other hand, the peak viscosity (PV), temperature at peak viscosity (P_{temp}), final viscosity (FV) and setback viscosity (SBV = FV-PV) values were representative of pasting properties of rice as illustrated in Table 3. The experimental results from Table 3 show that the drying temperatures of 60-100°C directly affected the gelatinization temperature of parboiled rice. Peak viscosity of parboiled rice sample dried with HA and IR sources were lower than those of the reference rice sample, which was dried by ambient air ventilation. This is due to retrogradation causing rice starch granule reassociation, that is, resistance against water absorption and little penetration inside the grain kernel. Thus the parboiled rice kernel required more energy for absorption and took a longer cooking time. These pasting properties were according to pasting of parboiled rice and shown in Table 3 and exhibit the same trend as in previous works (Taechapairoj *et al*., (2003); Tirawanichakul, 2004; Tirawanichakul *et al.*, 2004a; Soponronnarit *et al.*, 2008).

The results show that the pasting properties were significantly affected by drying temperature. The peak viscosity (PV), temperature at peak viscosity (P_{temp}), final viscosity (FV) and setback viscosity (SBV = FV-PV) values of parboiled rice flour are remarkably lower than those of the reference rice flour. This is because soaked rice after drying changed its paste properties and formed the complex structure of starch, lipid and protein (Soponronnarit *et al.*, 2008). The dried parboiling rice samples mostly changed only the outer side

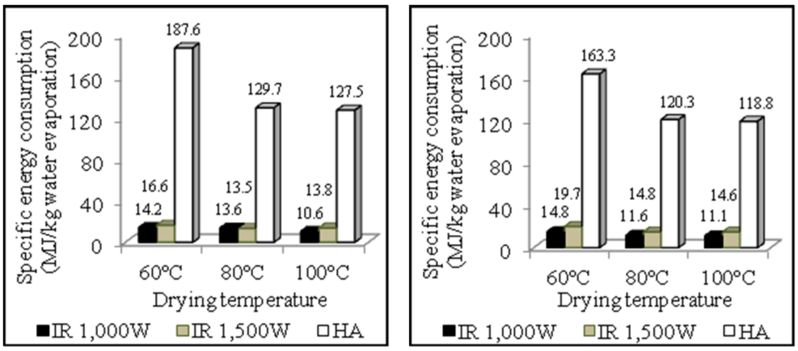
Table 3. Pasting properties of raw and parboiled rice flour

Source/Drying temperature (°C)		Peak viscosity (RVU)*	Trough 1*	Breakdown viscosity (RVU)*	Final viscosity (RVU)*	Setback viscosity (RVU)*	Peak time*	Pasting temperature* (°C)
Leb Nok Pattani (LNP)								
Raw rice (reference)		189.13[a]	145.05[a]	44.09[a]	251.00[a]	61.88[a]	5.93[f]	78.40[f]
Control rice		36.38[b]	35.71[b]	0.67[b]	50.46[b]	14.09[b]	8.60[e]	84.73[e]
HA	61.1	29.50[d]	29.33[d]	0.17[f]	37.33[e]	7.83[g]	8.87[b]	87.15[c]
	78.6	30.50[c]	30.25[c]	0.25[e]	39.50[c]	9.00[e]	8.93[a]	86.40[d]
	100.0	29.67[d]	29.25[d]	0.42[c]	38.58[d]	8.92[e]	8.67[d]	87.95[c]
IR 1,000 W	61.3	27.79[e]	27.55[e]	0.25[e]	37.00[e]	9.21[d]	8.74[c]	86.65[d]
	80.9	23.71[f]	23.54[f]	0.17[f]	31.79[g]	8.09[f]	8.84[b]	88.38[b]
	95.8	22.25[g]	22.13[g]	0.13[g]	30.13[h]	7.88[g]	8.97[a]	88.30[b]
IR 1,500 W	62.9	29.79[d]	29.33[d]	0.46[c]	39.84[c]	10.04[c]	8.67[d]	86.73[d]
	78.4	27.38[e]	27.00[e]	0.38[d]	35.21[f]	7.84[g]	8.70[c]	87.08[c]
	96.8	18.92[h]	18.79[h]	0.13[g]	25.46[i]	6.54[h]	8.93[a]	89.38[a]
Suphanburi 1 (SP 1)								
Raw rice (reference)		175.46[a]	136.58[a]	38.88[a]	272.09[a]	96.63[a]	5.67[e]	79.23[e]
Control rice		16.33[b]	16.00[b]	0.33[b]	20.75[d]	4.42[c]	8.73[b]	87.10[d]
HA	61.3	17.75[b]	17.5[b]	0.25[d]	22.08[c]	4.33[d]	8.67[c]	87.10[d]
	80.1	15.25[d]	14.25[d]	0.19[e]	26.75[b]	11.50[b]	8.60[d]	87.50[c]
	96.2	13.67	13.50[e]	0.17[e]	17.17[e]	3.50[f]	8.67[c]	87.90[b]
IR 1,000 W	57.1	16.38[b]	16.09[b]	0.29[c]	20.13[d]	3.75[e]	8.67[c]	87.10[d]
	80.7	14.50[e]	14.38[d]	0.13[f]	17.96[e]	3.46[f]	8.70[c]	87.80[b]
	96.4	12.58[f]	12.46[f]	0.13[f]	15.71[f]	3.13[h]	8.77[b]	87.90[b]
IR 1,500 W	65.2	15.92[c]	15.67[c]	0.25[d]	19.75[d]	3.83[e]	8.73[b]	87.15[d]
	80.9	14.58[e]	14.25[d]	0.33[b]	17.92[e]	3.33[g]	8.53[d]	87.95[b]
	91.6	12.50[f]	12.38[f]	0.13[f]	15.54[f]	3.05[i]	8.80[a]	88.68[a]

Note: The different letters within the same column show data has significant difference at confident percentage of 95% ($p<0.05$). Control rice is parboiled rice which is dried by ambient air ventilation. Raw rice or reference rice is fresh rice which is dried by ambient air ventilation

of the kernel whilst the inner side of grain kernel was not much affected by this rapid drying with IR source, especially at high drying temperature. These thermo-physical changes of the parboiled rice due to parboiling process have been also observed in the previous works via the pasting properties (Soponronnarit *et al.*, 2008; Donludee *et al.*, 2009). The peak viscosity of rice flour prepared from conventionally aged rice was also found to be lower than that of freshly-harvested rice (Indhudhara *et al.*, 1978). These pasting property occurrences in the present study showed is similar trend to that of the conventional aged paddy (Nakakete and Noomhorm, 2001; Inprasit and Noomhorm, 2001). By these effects, the parboiled rice gives relative high head rice yield, which has been discussed above. Moreover, the high pasting temperature of parboiled rice sample in all heat sources compared to the reference rice sample was probably due to the results of starch gelatinization and formation of amylose–lipid complexes, which occurred during parboiling thermal treatment. Then the gel formation might resist water penetration with consequent increasing of temperature for starch swelling (Juliano, 1985). In the present study, the pasting temperatures of LNP rice variety and SP 1 rice variety was in the ranges of 86.40-89.38°C and 87.10-88.68°C. For the setback viscosity evaluation, the results showed that parboiled rice drying has a low setback value compared to the reference rice, implying that the parboiled rice after drying had a less firmness in texture than that of the reference rice, corresponding to the previous work (Donludee *et al.*, 2009).

By ANOVA analysis, the results imply that the ability of parboiled starch granules to rupture after cooking is reduced (as indicated by the decrease in breakdown viscosity value in Table 3) significantly by aging of the granules. The effect of IR drying on pasting property is also represented in Table 3. The results showed that pasting property of parboiled rice using IR drying was different from that using HA drying. Most of the PV, BKV and FV values were



(a) Leb Nok Pattani (LNP) rice (b) Suphanburi 1 (SP 1) rice

Figure 5. The specific energy consumption of parboiled rice drying versus drying temperatures of 60-100°C (a) Leb Nok Pattani rice and (b) Suphanburi 1 rice variety

lower than that with HA drying. In addition, it can be concluded that the medium-grain and long-grain parboiled rice drying with HA and IR technique in temperatures ranging of 60-100°C had a significant effect on the pasting temperature of rice and can accelerate the aging of rice variety as with drying at high temperatures over 100°C (Noomhorm *et al*., 1997, Donludee *et al*., 2009).

3.3 Specific energy consumption

The specific energy consumption (SEC) was determined by following Eq. (2) as illustrated in Figure 5. The results showed that the SEC decreased when the drying temperature increased. This result in the same trend as in other previous works related to drying of biomaterial and grain kernel. Moreover, the parboiled rice using IR technique at power inputs of 1,000 W and 1,500 W had lower energy consumption than other HA dryings at all drying temperatures of 60-100°C. This is because infrared wave radiation could penetrate into the interior of the parboiled rice. By this radiative heat transfer for parboiled rice drying, the electromagnetic IR wave is converted to thermal energy to assist a more rapid heating mechanism. From the graph in Figure 5, the SEC value of LNP and SP 1 rice drying with IR of 1,000 W and drying temperature of 100°C had a lower energy consumption compared to the other drying strategies and this IR drying technique for parboiled rice should be promoted. Thus it is concluded that the parboiled rice drying with IR technique is an efficient technique for medium-grain and long-grain parboiled rice varieties.

4. Conclusion

The parboiling process using hot air drying and infrared drying was carried out. The results show that parboiled medium-grain and long-grain rice drying can have enhanced physical property in terms of head rice yield, yellowing and pasting property by IR drying with temperature between 60 and 100°C. However, for getting a high-efficiency parboiling process, soaking at a temperature of 70°C for 3 and 4 h for medium-grain Leb Nok Pattani rice and long-grain Suphanburi 1 rice, respectively, ambient air tempering for 24 h and steaming for 30 min and IR should be promoted, especially any IR power of 1,000W and drying temperature of 100°C.

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