สมบัติเชิงฟิสิกส์ความร้อน และปัจจัยของสนามไฟฟ้า ต่อขบวนการอบแห้งและคุณภาพของข้าวเปลือกเมล็ดสั้น

Thermo-Physical Properties and Effect of Electrical Field on Drying Process and Quality of Short-grain Paddy

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บทคัดย่อ

พารามิเตอร์ทางฟิสิกส์เชิงความร้อนและปัจจัยของความเข้มสนามไฟฟ้าที่มีต่อจลนพลศาสตร์ของการอบแห้งและคุณภาพของข้าวเมล็ดสั้นสายพันธุ์สังข์หยดถูกนำเสนอในงานวิจัยนี้ ค่าความหนาแน่นปรากฏ ความจุความร้อนจำเพาะ ร้อยละของถูกศึกษาภายใต้เงื่อนไขร้อยละความชื้นระหว่าง 25 ถึง 35 มาตรฐานแห้ง ขณะที่ค่าความชื้นสมดุลของข้าวถูกศึกษาภายใต้อุณหภูมิแวดล้อมในช่วง 40-70°C ซึ่งสารละลายเกลืออิ่มตัวทำให้เกิดความชื้นสัมพัทธ์ได้ร้อยละ 10-90 ผลการทดลองได้นำมาหาความสัมพันธ์ของพารามิเตอร์ต่างๆ กับค่าความชื้นเริ่มต้น อุณหภูมิ เพื่อสร้างสมการอธิบายผลการทดลองด้วยเทคนิคการถดถอย โดยเลือกสมการที่ให้ค่าสัมประสิทธิ์การตัดสินใจ (R^2) สูงสุด และมีค่าความผิดพลาดรากที่สองกำลังสองเฉลี่ยต่ำสุ (RMSE) ผลการทดลองพบว่า ค่าความหนาแน่นปรากฏ ค่าความจุความร้อนจำเพาะและร้อยละช่องว่างของข้าวสังข์หยดมีความสัมพันธ์เชิงเส้นกับค่าความชื้นเริ่มต้นของตัวอย่าง ขณะที่สมการแบบจำลองของ Henderson สามารถใช้อธิบายผลของความชื้นสมดุลได้ดีที่สุด โดยพบว่าค่าความชื้นสมดุลจะเป็นฟังก์ชันกับค่าความชื้นสัมพัทธ์และอุณหภูมิของอากาศแวดล้อม

ในการศึกษาอัตราการอบแห้งโดยการดิสชาร์จไฟฟ้าที่ความเข้มสนามไฟฟ้าในช่วง 6-10 kV_{ac} ก่อนการอบแห้ง พบว่า อัตราการอบแห้งของข้าวเปลือกหลังการดิสชาร์จจะมีค่าสูงกว่าอัตราการอบแห้งปกติที่ไม่มีการดิสชาร์จ และที่ระยะเวลาดิสชาร์จไฟฟ้านานขึ้น จะมีความสิ้นเปลืองพลังงานมากกว่าการใช้เวลาดิสชาร์จไฟฟ้าสั้น และหากใช้อุณหภูมิอบแห้งที่ต่ำ จะไม่ส่งผลอย่างมีนัยสำคัญต่อค่าร้อยละข้าวเต็มเมล็ดและร้อยละการงอกของข้าวเมล็ดสั้น โดยไม่ควรใช้อุณหภูมิอบแห้งสูงกว่า 50°C

Abstract

Determination of thermo-physical parameters and high electric field affecting to drying kinetic and quality of short-grain *Sung Yod* paddy was presented in this work. Apparent density, specific heat capacity and void fraction with initial moisture contents of 25-35% dry-basis (d.b.) while the equilibrium moisture content were evaluated among surrounding temperatures of 40-70°C corresponding to relative humidity of 10-90%. In addition, the relationship of these thermo-physical parameters, drying temperatures and initial moisture contents were mathematical simulated by regression method. The coefficient of determination (R^2) and root mean square error (RMSE) values were used as the criterion for selecting the best equation to describe the experimental results. The results showed that the apparent density, specific heat capacity and percentage of void fraction had linear relation with initial moisture contents of paddy. The simulated value of equilibrium moisture content (EMC) by

Henderson’s model was the best fitting with the experimental results and the EMC value was function of surrounding temperature and relative humidity.

For investigating of the drying rate of paddy after treatment by a high voltage electric field (HVEF) of 6-10 kV_{ac} at electrical discharge time of concluded that the HVEF slightly accelerated the drying rate of short-grain *Sung Yod* rice variety. In addition, the quality analysis showed that the HVEF value had insignificant effect to percentage of germination ($p<0.05$) and the whiteness value of rice corresponding to the previous work. The head rice yield of dried rice increased with a decreasing HVEF value and drying temperature. The recommend drying temperature for maintaining high germination should be not higher than 50°C.

1. Introduction

Fresh rough rice after harvesting normally has a high level of moisture content over 20% dry-basis. This moisture content level let the paddy risk to biodegrade. So the fresh paddy needs to be appropriate dehydrated until the final moisture content reaches 15-16% dry-basis [1, 2], especially during storage in rainy season. A proper post-harvesting management can maintain the quality of rice for a prolonged storage period without disturbances from bacteria and fungi, metabolic activities [3, 4]. The application of electrical treatments in agro-industrial processes has shown a sustained progression in recent decades such as fruit storage, food dehydration and preservation [2-8]. Moreover, there is growing interest in the application of non-thermal processing of food and similar materials. High voltage electric field (HVEF) method is a novel non-thermal technique of drying and is being developed recently and however, there are a few reports available on HVEF principal compared to conventional drying technologies based on conductive, convective and radioactive heat treatment. The non-thermal electrical discharges are excellent sources of ideal energetic electrons with 1-10 eV and possible high density depending on their applications.

Laroussi *et al.* (1999) [10] and Montie *et al.* (2000) [11] also reported that for *E.coli*, the outer membrane were ruptured after a short non-thermal plasma exposure (10–30 s), followed by leakage of their cytoplasm. In addition, for longer plasma exposure times, total cell fragmentation was reported. This was due to the rapid rupture of the membrane of gram-negative bacteria caused by the fatty-acid peroxide formation, corresponding to Mendis *et al.* [12]. Recently, Cao *et al.* [1, 2] reported that the corona discharge produced by a multiple point-to-plate was used to enhancing of rough rice drying. The result showed that the corona discharges have an effect on the rice fissuring and germination. Normally, grain drying in post-harvesting is practiced to maintain the quality of grains, to prevent the growth of bacteria and fungi, and to prevent metabolic activities and the development of disinfection by insects and mites during storages period. Consequently, the final moisture content of paddy should be lower than 16% dry-basis [3, 4].

Therefore, the objectives of this work were to study the thermo-physical properties and high voltage electric field affecting the drying rate and the quality of paddy. Physical qualities were also determined in terms of head rice yield, rice whiteness, and percentage of germination.

2. MATERIALS AND METHOD

2.1. Materials

The fresh paddy varieties provided by the Rice Research Institute at Pattalung Province, Thailand, were rewetted, mixed and kept in a cold storage at a temperature range of 4-6ºC for a week. The desired initial moisture content of paddy was in the range of 25-35% dry-basis (d.b.). The *Sung Yod* rice varietiy, was used for this research. Before starting the experiments, the paddy was placed in ambient environment until grain temperature was close to ambient air temperature.

2.2 Determination of equilibrium moisture content (EMC)

For determining EMC value, the five saturated salt solutions for achieving an EMC stage used in this experiments such as KNO_3, NaCl, $Mg(NO_3)_2{\bullet}6H_2O$, $MgCl_2{\bullet}6H_2O$ and LiCl. All of the saturated salt solutions can provide relative humidity of 10-90%. During experiments, the paddy samples and salt solutions were put in the airtight vials. The vials was placed into incubator at controlled temperatures of 30 to 70°C to obtain dry matter weight. The surrounding temperature and ambient air conditions were measured by K-typed thermocouple connected to a data logger. After a few week, sample was in an equilibrial state with salt solution. This state was acknowledged when three consecutive weight measurements showing a difference lower than 0.001 g. Then the sample was taken to determine moisture content followed by AOAC method [13]. The sample was taken by means of triplication. Finally, the six isotherm models for predicting EMC were formulated to fit relationship between the experimental data of EMC, surrounding temperature (T) and the relative humidity (RH) such as the Chung and Pfost’ equation , Henderson's equation and Halsey’s equation. Formulated functions of relative humidity, temperature and EMC conditions are written as follows:

(1) Chung and Pfost’ equation (1967)

$$\ln RH = \frac{-A}{RT}\exp(-BM_{eq}) \tag{1}$$

(2) Henderson's equation (1952)

$$1 - RH = \exp(-ATM_{eq}^{B}) \tag{2}$$

(3) Halsey's equation (1948)

$$RH = \exp(\frac{-A}{RT}M_{eq}^{B}) \tag{3}$$

(4) Modified Chung and Pfost

$$\ln RH = \frac{-A}{R(T + C)} \exp(-BM_{eq}) \tag{4}$$

(5) Modified Henderson

$$1 - RH = \exp(-A(T + C) M_{eq}^{B}) \tag{5}$$

(6) Modified Halsey

$$RH = \exp\left[\frac{-A}{R(T + C)}\right] M_{eq}^{B}) \tag{6}$$

where M_{eq} is the equilibrium moisture content, % d.b., R is the universal gas constant, 8.314 J/mole-K, RH is the relative humidity, decimal, T is the absolute temperature, K and A, B,C is the constant value.

2.3 Thermo-physical properties

2.3.1 Apparent density (ρ)

An apparent density is the ratio of the mass sample of the paddy to its total volume. Considering the apparent density, the mass of samples were weighted by an electronic balance with an accuracy of ±0.01 g and volume was measured using a volumetric flask. Then the apparent density was calculated by the following equation:

$$\rho = \frac{m}{V_b} \tag{7}$$

where ρ is the apparent density (kg/m^3), m is the weight of paddy (kg), V_b is the volume of paddy (m)

2.3.2 Void fraction (ε)

The porosity of paddy is the fraction of the void in the bulk paddy. The porosity was calculated by the following equation:

$$\varepsilon = \frac{V_{Oil}}{V_b} \times 100 \tag{8}$$

where ε is the porosity (%), V_{oil} is the volume of oil (m), V_b is the volume of paddy (m^3)

2.3.3 Specific heat capacity (c_p)

The specific heat capacity of the sample was determined using a colorimeter at moisture contents of 25-35% dry-basis. The equilibrium temperature was recorded by data logger and the specific heat of sample was calculated by the following equation:

$$c_p = -\frac{[m_c c_c (T_{eq} - T_{ci}) + m_w c_w (T_{eq} - T_{wi})]}{m_p (T_{eq} - T_{pi})} \tag{9}$$

where c_p is the specific heat of paddy, kJ/kg^{O}C; c_c is the specific heat of colorimeter, kJ/kg^{O}C; c_w is the specific heat capacity of water, kJ/kg^{O}C; m_c is the mass of colorimeter, kg; m_p is the mass of paddy, kg; m_w is the mass of water, kg; T_{eq} is the equilibrium temperature, ^{O}C; T_{ci} is the initial temperature of colorimeter, ^{O}C; T_w is the initial temperature of water, ^{O}C; T_{pi} is the initial temperature of paddy, ^{O}C.

2.4 The high voltage electrostatic field system and the drying system.

A multiple points-to-plate high voltage electrostatic field (HVEF) system for paddy drying was conducted as shown in Figure 1. The 300 sharp needles and plate were supplied using the high voltage power supply of 0-15 kV. The electric potential difference and discharge current between both electrodes was measured by a high voltage probe (Tektronix model 6615B) and a current probe (Tektronix model CT-1), respectively. The thin-layer drying system comprised of a 1x3 kW electric heating unit, a backward curved blade, cylindrical shaped drying chamber and a centrifugal fan which was driven by a 1.5 kW motor.

2.5 Drying experimental

A fresh paddy sample weighing of 0.8 kg was placed in an aluminum tray and was then put on the grounded plate as shown in figure 1. The sample was treated with the HVEF value of 6, 8 and 10 kV while discharge gap was fixed at 2.0 and 3.0 cm. The electrical discharge time was varied from 20 and 40 min. After HVEF treatment, the rice sample was thin-layer dried at the drying temperature of 40-70^{O}C and air flow rate of 1.9$\pm$0.1 m/s. The control rice sample was prepared in the same drying conditions without HVEF treatment. The desired final moisture content of dried rice was 22.5$\pm$2.0% d.b. The moisture content of rice sample was determined by the AOAC standard method [13]. The grain temperature, dry bulb and wet bulb of ambient air and inlet drying air temperature were continuously measured by a typed-k thermocouple connected to a data logger (Yogokawa model PX100).

2.5 Quality of rice

The qualities of the rice samples after drying were determined and compared to the control rice sample. The various qualities of paddy were evaluated as follows

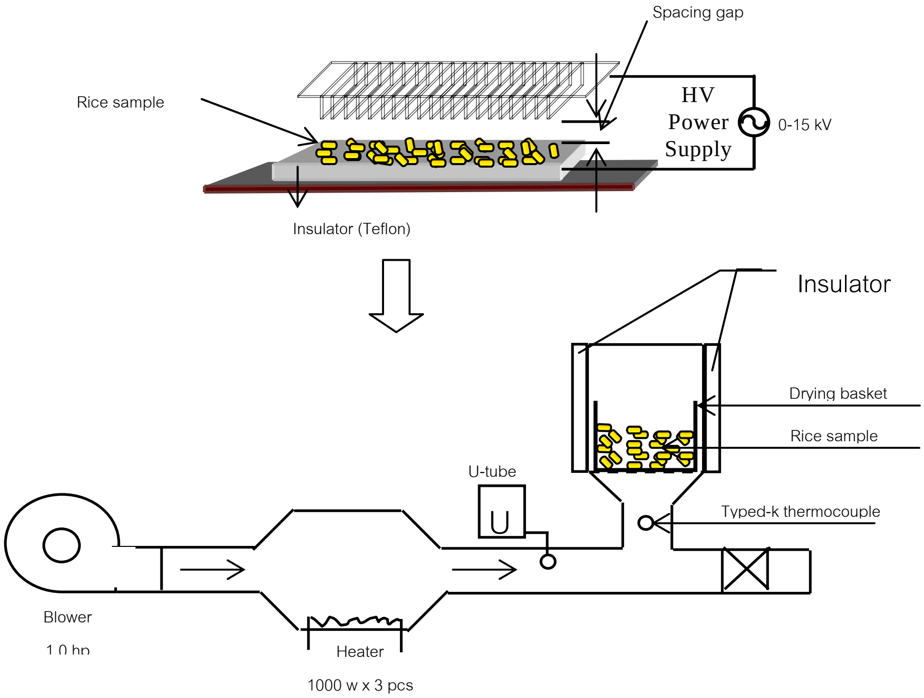

Figure 1 Illustrative of the HVEF system (top) and the thin-layer drying system (bottom).

Head rice yield and germination

The determination of head rice yield (HRY) was performed according to the Rice Research Institute, Patthalung Province, Thailand. HRY is defined as the ratio of mass of head rice obtained from milling to mass of paddy at the beginning. This value was determined in duplicate. For determination germination of paddy, the method was followed by the Rice Research Institute principle.

2.6 Specific energy consumption

Specific energy consumption was defined as the energy required removing a unit mass of water in drying the paddy from its initial moisture contents of 24.2 to 34.8% dry-basis to the desired final moisture content of 22.5 ±0.2% dry-basis. The total energy consumption was calculated as the sum of the energy consumed by the HVEF treated and hot air drying. The specific energy consumption was expressed as MJ/kg of water evaporated.

2.7 Data analysis

Quality differences between the treated and control sample were determined using analysis of variance (ANOVA) and Duncan's multiple range tests at the 5% probability level ($p \leq 0.05$). The constant values in these models were determined by the non-linear regression analysis from the experimental data. The coefficient of determination (R^2) and root mean square error (RMSE) values were used as the primary criterion for selecting the best equation to describe the experimental data. The following equations were written as:

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (MR_{exp} - MR_{cal})^2}{\sum_{i=1}^{N} (MR_{exp} - \overline{MR_{exp}})^2} \qquad (10)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (MR_{exp} - MR_{cal})^2} \qquad (11)$$

where MR_{exp} is the experimental moisture ratio (decimal), MR_{cal} the predicted moisture ratio (decimal) and N is the number of observations, respectively.

3. RESULTS AND DISCUSSION

3.1 Equilibrium moisture content (EMC)

The values of equilibrium moisture content constants and coefficients of different models of *Sung Yod* paddy was shown in Table 1 showed that EMC equation was a function of relative humidity and absolute temperature.

The EMC equation of *Sung Yod* paddy, Henderson's equation has good relation to the experimental values (R^2 = 0.973), corresponding to its lowest RMSE value compared to the others. Figure 2 illustrates the relationship between the equilibrium moisture content and relative humidity of *Sung Yod* paddy samples at surrounding temperature of 60°C. The result showed that equilibrium moisture content increased when the relative humidity of air surrounding increased. This is because the water content of rice sample rarely transfers to surrounding among high humidity environment. The same evidences have been reported in the other grain kernel and cereal grain [14].

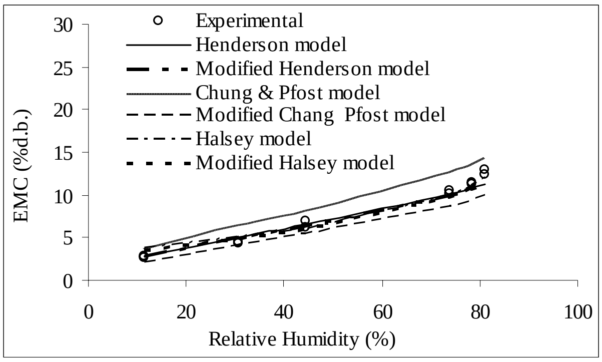

Figure 2 The EMC value of experimental results versus simulated models among relative humidity of 30-80% variety at drying temperatures of 60°C.

3.2 Thermo-physics prosperity

3.2.1 Apparent density (ρ)

The results showed that the apparent density of *Sung Yod* paddy linearly related to the moisture content. The equation can be expressed by the following equation:

$\rho = 575.18 + 8.69M$ (12)

$R^2 = 0.977$ RMSE = 0.332

3.2.2 Void fraction (ε)

The percentage of void fraction of *Sung Yod* paddy linearly related to the moisture content. From the results, the formulated equation by linear regression analysis and the relationship between percentage of void fraction can be expressed as follows:

$\varepsilon = 83.77 - 1.03\ M$ (13)

$R^2 = 0.981$ RMSE = 0.601

3.2.3 Specific heat capacity

The specific heat capacity of *Sung Yod* paddy was observed to linearly relate to the moisture content. The relationship can be expressed by the following equation:

$c_p = 0.020M + 3.726$ (14)

$R^2 = 0.991$ RMSE = 0.068

3.3 Determination the quality

3.3.1 Physical quality

Head rice yield of rice

Table 2 shows the head rice yield of *Sung Yod* paddy at three different initial moisture contents, 24.5, 28.6 and 34.6 % d.b. The air flow rate was fixed at 1.9 m/s and the drying air temperature was in the range of 40-50°C. The results showed that head rice yield of *Sung Yod* paddy compared to the reference sample were between 46.6 and 53.6 implying that the HVEF treatment with enhanced paddy drying at a low inlet air temperatures of 40°C and 50°C have an insignificant effect on the qualities of the rice.

In contrary, drying at a drying temperature over 50°C and HVEF pretreatment could not maintain high head rice yield. This was because high temperatures cause the formation of fissure inside the paddy kernels according to Tirawanichakul *et al*. [4].

Table 1 Values of equilibrium moisture content constants and coefficients of different models of Sung Yod rice varieties in various temperature ranges of 30 to 60°C and relative humidity of 11.2-89.0%

Model	Constant value			R^2	RMSE*
	A	B	C		
Chung and Pfost (1967)	13909.98	27.669	-	0.947	1.018
Henderson (1952)	0.325	1.912	-	0.973	0.700
Halsey (1948)	8.073	-2.013	-	0.965	2.963
Modified Chung and Pfost	4052.53	30.218	235.483	0.969	1.322
Modified Henderson	0.512	1.914	114.681	0.973	2.515
Modified Halsey	3.917	-2.003	166.219	0.967	2.964

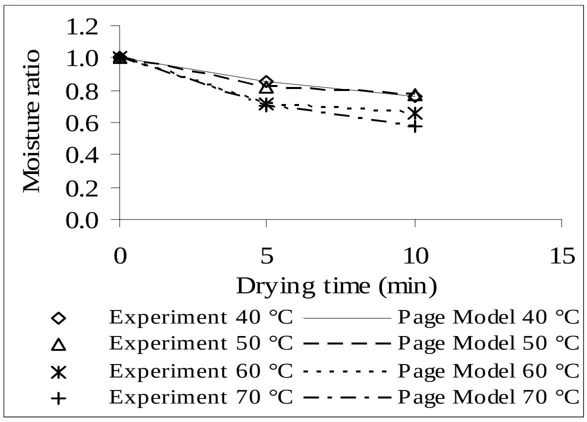

Figure 3 Moisture profile of *Sung Yod* paddy variety with drying time (HVEF of 8 kV; discharge gaps of 2 cm and discharge time of 20 min; drying temperatures of 40-70°C, air flow rate of 1.9 m/s and initial moisture content of 24.5% d.b.).

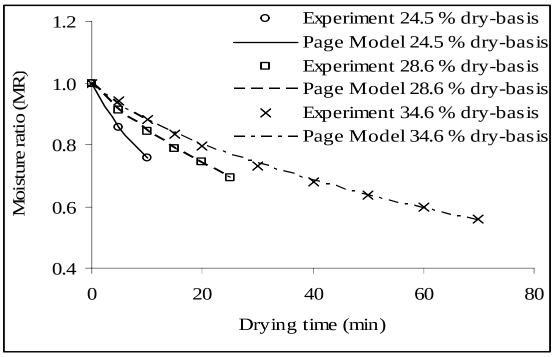

Figure 4 Evolution of moisture profile of *Sung Yod* paddy variety with drying time (HVEF of 8 kV; discharge gaps of 2 cm and discharge time is 20 min; drying temperatures of 40°C; air flow rate was 1.9 m/s and initial moisture content 24.5-34.6% d.b.).

3.3.2 Chemical quality

Based on the determination of the chemical quality of *Sung Yod* paddy varieties, the results showed that paddy drying with temperature of 40-70°C and pretreatment by the HVEF could enhance drying rate of rice samples. Moreover, the initial moisture content of the rice sample had no significant effect on amylose content, protein and total fat content ($p<0.05$). The average amylose content, total fat value and protein content of rice was 14.2±0.2%, 1.5 ±0.1% and 8.2±0.1%, respectively.

Table 2 The head rice yield (HRY) value of dried *Sung Yod* paddy with HVEF pretreatment at 8 kV, initial moisture content of 24.5-34.6 % dry-basis, air flow rate of 1.9 m/s and drying air temperature of 40-70°C

Drying temperature (°C)	*Condition (discharge time) (min)*	*Head rice yield (% HRY)*		
		24.5 %d.b.	*28.6% d.b.*	*34.6 % d.b.*
Reference		53.63^{m}		
40	*Control*	50.22^{j}	50.46^{i}	50.16^{j}
	20	51.15^{k}	50.77^{k}	50.41^{k}
	40	51.65^{l}	51.15^{l}	50.54^{l}
50	*Control*	49.66^{e}	49.74^{e}	46.55^{a}
	20	49.98^{h}	49.77^{f}	48.46^{c}
	40	50.01^{i}	50.61^{j}	49.35^{g}
60	*Control*	48.52^{b}	48.31^{a}	48.58^{d}
	20	49.21^{d}	49.15^{c}	49.11^{e}
	40	49.95^{g}	49.83^{g}	49.75^{h}
70	*Control*	48.02^{a}	48.58^{b}	48.11^{b}
	20	49.12^{c}	49.37^{d}	49.3^{f}
	40	49.71^{f}	49.92^{h}	49.82^{i}

Note: Control means rice sample was dried under the same drying condition by without the high voltage electric field treatment. Reference means rice sample was dried by ambient air ventilation. The different superscripts in the column denote the significant difference ($p< 0.05$).

3.4 Specific energy consumption

The specific energy consumption of all experiments was determined and is shown in figure 6. Additionally, it was found that the specific energy consumption was independent to the drying with the HVEF treatment, while it was depended on the drying air temperature. Figure 6 shows the effect of the discharge time (20 and 40 min) and drying air temperature (40-70ºC) on the specific energy consumption of the system. The results showed that the specific energy consumption slightly increased with increasing discharge time while the specific energy consumption can be achieved compared to the control sample, especially when drying at low drying air temperature.

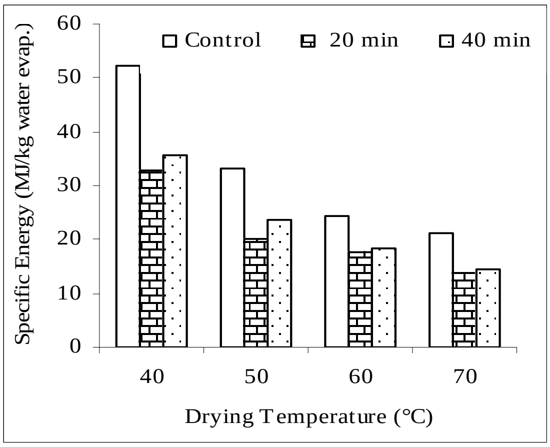

Figure 6 Specific energy consumption of Sung Yod rice variety with drying air temperature (high voltage electrical field of 8 kV; discharge gaps of 2 cm, and discharge time is 20 and 40 min; drying air temperatures of 40-70°C, air flow rate of 1.9 m/s and initial moisture content of 24.5% dry-basis).

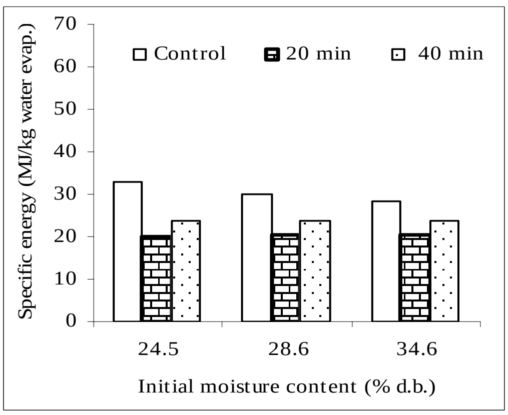

Figure 7 Specific energy consumption (SEC) of *Sung Yod* paddy variety at three different high voltage electrical fields of 8 kV; a discharge gap of 2 cm and three different discharge times of 20 and 40 min, a drying air temperature of 50°C, an air flow rate of 1.9 m/s and an initial moisture content of 24.5-34.6% dry-basis.

Figure 7 shows the effect of electrical discharge time and initial moisture content (24.5, 28.6 and 34.6% dry-basis) on specific energy consumption for paddy drying at certain temperature of 50°C. The paddy pretreated by two electric discharge times of 20 and 40 min was studied compared to the control dried paddy without pretreatment of electric discharge. The results showed that paddy pretreated by electric discharge consumed energy slightly lower than paddy without electric discharge pretreatment. Additionally the specific energy consumption of paddy drying with pretreatment at long electric discharge time (40 min) relatively high compared to the pretreatment with short electric discharge time (20 min). This is because the pretreatment of paddy by high electric field discharge let the air particle and water vapor between electrode gap activates. Then the collision and ionization of originally neutral molecules takes place resulting in input of the localized energy and evaporation of the water from the paddy kernel [15, 16]. However, it must consider to energy consumption. In this work the conclusion is that pretreatment using discharge time of 20 min for short-grain paddy is suitable condition.

4. CONCLUSION

The following conclusions were drawn from this study:

1. Head rice yield (HRY) was affected by the drying air temperature over 60°C. It concluded that HRY value inversely related to drying air temperature.
2. High voltage electric field pretreatment had insignificant effect to the germination of dried short-grain paddy physical dried by drying temperature below 60°C.
3. The specific energy consumption depends on the inlet drying air temperature and initial moisture content while the specific energy consumption slightly increases when the discharge time increases.

5. ACKNOWLEDGMENTS

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