As a consequence, the grain circulation on the other hand the rate of paddy entrained from the downcomer into the spout region would be improved. However, increase of feed rate with unchanging of dryer volume resulted in the decrease of residence time. Fortunately, gaining the higher grain circulation rate could compensate this and hence the increase in the ratio of the spouting period and the tempering period in downcomer should lead to enhancing of moisture reduction ability.

CONCLUSION

The prototype was shown to be a desirable feature of spouted bed as well as capability of continuous drying and offering consistent results throughout the testing periods. With assisting of tempering process in downcomer, the drying kinetics in the spout performed well, and resulted in satisfactory moisture reduction. No significant change in head rice yield was observed even the moisture content was reduced to 18% dry basis, nevertheless, using high inlet temperature up to 146°C. The whiteness was also acceptable. Finally, to overcome the problems of low feed rate (<1000 kg/h) and high thermal energy consumption, the influence of enhancing those of air flow rate and pressure should be studied.

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Development of a Commercial Scale Vibro-Fluidized Bed Paddy Dryer

Somboon Wetchacama, Somchart Soponronnarit and Wuttikon Jariyatontivait

ABSTRACT

The objectives of this research were to design, construct and test a prototype of vibro-fluidized bed paddy dryer with a capacity of 2.5–5.0 tons/h. Experimental drying conditions were: air flow rate 1.7 m^3/s (1.9 kg/s), bed velocity 1.4 m/s, average drying air temperature 125–140°C, residence time of paddy approximately 1 minute, bed height 11.5 cm, fraction of air recycled 0.85 (1.6 kg/s) and vibration of intensity 1 (frequency 7.3 Hz and amplitude 5 mm.). It was found that moisture content of paddy was reduced from 28 to 23 % d.b. at a feed rate of 4821 kg/h. Electrical power consumption and average diesel oil consumption were 9646 W and 17.6 l/h, respectively. Specific primary energy consumption was 6.15 MJ/kg-water evap. Electrical power of blower motor and vibrator motor was 55 % as compared to electrical power of blower motor used in fluidized bed drying without vibration. For operation of 12 hours/day and 90 days/year, paddy drying cost was 1.50 baht/kg-water evap. (fixed cost 0.50 baht/kg-water evap. and operating cost 1.00 baht/kg-water evap., US$ 1 = 40 baht).

Key words : drying cost, head rice yield, paddy, rice whiteness, vibro-fluidization

INTRODUCTION

Soponronnarit and Prachayawarakon (1994) studied drying of high moisture content paddy using fluidization technique. The factors, which affected paddy quality after drying and energy consumption, were investigated. The experimental conditions were as follows: drying air temperature 100–150°C, specific air flow rate 0.13–0.33 kg/s-kg dry matter and initial moisture contents of paddy 28.4–40 % d.b. The result showed that drying rate increased with specific air flow rate and/or temperature of drying air. Energy consumption decreased when specific air flow rate increased or fraction of air recycled increased. The suggestions to obtain good paddy quality were: drying air temperature should not be higher than 115°C and moisture content of paddy after drying should not be lower than 24 –25 % d.b. (mainly considered in head rice yield and rice whiteness qualities). The study and development of paddy using fluidization technique was continued and succeeded in 1996, a prototype of fluidized bed dryer was constructed. The commercial fluidized bed dryers with capacities of 5 and 10 tons/h were constructed and had been sold since the beginning of 1996. The conditions of paddy drying were as follows: drying air temperature in range of 120–150° C, drying air velocity approximately 2–2.3 m/s and fraction of air recycled approximately 0.8.

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Rysin and Ginzburg (1992) studied food product drying using vibro-fluidization technique. It was found that vibration intensity ($A\omega^2/g$) should be lower than 3.3. The suitable values of vibration intensity and amplitude were 1.5–2.0 and 5–10 mm, respectively. Ringer and Mujumdar (1982) designed a chart, which provided to aid in the selection of the operating parameters of drying by using vibro-fluidization technique (the ratio of drying air velocity to minimum fluidization velocity and vibration intensity not more than 1.1 and 3.3, respectively.). Han *et al.* (1991) studied the residence time distribution and drying characteristics of a continuous pilot-plant vibro-fluidized bed dryer. Wheat particles and BYN (trade name Biyanning, a medication for rhinitis) were used as testing materials. Operating variables in the study included vibration intensity, mass flow rate of air, material feed rate, inlet air temperature, and particle size. The flow of particles in the dryer was considered as plug flow. From the results, it was found that vibration intensity was the most significant factor affecting particle mean residence time, particle diffusion and constant drying rate. As vibration intensity increased, mean residence time decreased and drying rate increased.

From the past research, it can be concluded that the appropriate operating conditions of paddy drying using fluidization technique to obtain good paddy quality were as follows: moisture content of paddy after drying not lower than 23 % d.b., bed height of 10–15 cm, drying air temperature not higher than 150°C. For drying using vibration fluidization technique, it was recommended that vibration intensity and amplitude should be in range of 1.0–3.3 and 5–10 mm, respectively, and low frequency should be used to avoid the deterioration of vibration system.

According to the success of producing the commercial fluidized bed paddy dryers which have been sold in Thailand and exported to various countries and the requirement to reduce electrical power of blower motor, the objectives of this research are therefore to design, construct, and test a commercial-scale vibro-fluidized bed paddy dryer with capacity of 2.5–5 tons/h (suitable for rice mill), expecting that it can reduce electrical power of blower motor by applying vibration technique with fluidization technique.

MATERIALS AND METHODS

A vibro-fluidized bed paddy dryer with capacity of 5 tons/h was fabricated by Rice Engineering Supply Co., Ltd. and tested at Thanyakanwangtaphet Rice Mill, Suphanburi province, Thailand. The unit comprised of a diesel burner and combustion chamber, a backward curved blade centrifugal fan driven by a 7.5 kW motor, 0.6 × 2.1 × 1.2 m drying section, and 0.6 × 2.1 m perforated steel sheets with 0.5 mm thickness and 1.1 cm diameter hole. The vibration systems comprised of cams, coil springs, watch springs, 1.5 kW vibrator (frequency of 7.3 Hz, vibration intensity of 1 and vertical amplitude of 5 mm), hopper, rotary feeder, rotary discharger, recycle air pipe and cyclone, the details as shown in Figures 1(a) and 1(b).

During drying, paddy samples before and after drying were kept every 20 minutes to investigate moisture and test quality. Before testing of paddy quality, paddy samples were blown with ambient air until moisture content decreased to approximately 14 % w.b. The positions for temperature and air velocity measurement were shown in Figure 1(a). Temperatures were measured by a thermocouple, type k, connected to a data logger with an accuracy of ± 1°C. Air velocities were measured by a hot wire anemometer with an accuracy of ± 4 % and electrical power was measured by a clamp-on meter with an accuracy of ± 0.5 %.

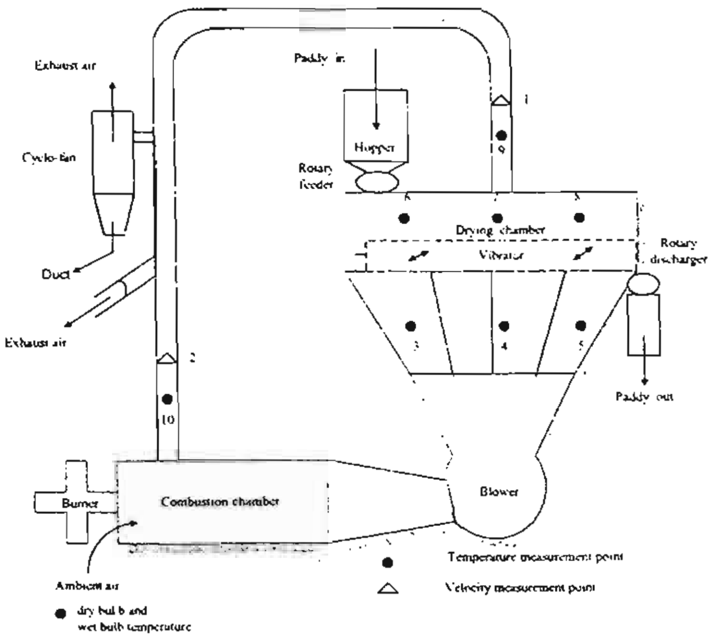

Figure 1(a) Diagram showing a vibro-fluidized bed paddy dryer.

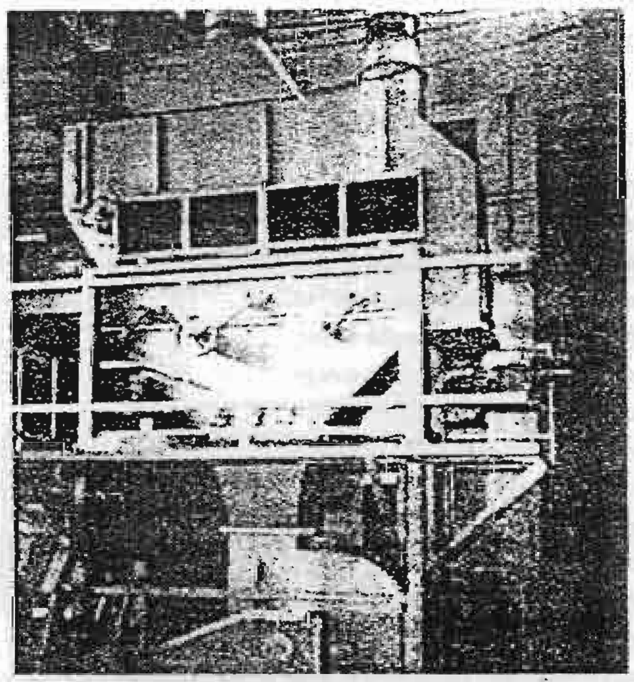

Figure 1(b) Photograph showing a vibro-fluidized bed paddy dryer.

RESULTS AND DISCUSSION

In this research, vibro-fluidized bed dryer was tested. The paddy drying conditions were as follows: paddy feed flow rate of 4.82 tons/h, drying air flow rate of 1.7 m^3/s (velocity of air in drying chamber was 1.4 m/s), fraction of air recycled of 0.85, drying air temperature in range of 125–140 °C and vibration intensity of 1 (frequency of 7.3 Hz and vertical amplitude of 5 mm). Experimental results shown in Table 1.

Moisture content of paddy and temperature in drying chamber

Figure 2 shows the values of temperature at various points of dryer. In case of average inlet air temperature of 140°C, average temperature and relative humidity of ambient air were 35°C and 66 %, respectively. It was found that average paddy temperature at drying chamber outlet was 64°C. Figure 3 shows the inlet and outlet moisture contents of paddy, the average values were 28 and 23 % d.b., respectively.

Paddy quality

In order to investigate the percentage of head rice yield, paddy samples before and after drying were kept every 20 minutes. It was found that average percentages of head rice yield of paddy samples, which were dried by ambient air, and vibro-fluidized bed dryer (in case of average inlet drying air temperature was 140°C) were 32.0 and 37.0, respectively. Head rice yield obtained from ambient air drying was approximately 5 % lower, as shown in detail in Figure 4. This resulted from high enough initial moisture content of paddy as well as from using suitable drying air temperature (140°C) within short drying period (approximately 1 minute). Consequently, partial gelatinization occurred in paddy kernel, which was the same as the results from the study of paddy drying using

Table 1 Performance of vibro-fluidized bed paddy dryer (bed height = 11.5 cm, bed velocity = 1.4 m/s, vibration intensity = 1, fraction of air recycled = 0.85 and feed rate = 4821 kg/h).

Drying air temperature (°C)	Initial moisture content (% d.b.)	Final moisture content (% d.b.)	Paddy temperature at dryer outlet (°C)	Head rice yield from ambient air drying (%)	Head rice yield from fluidized bed drying (%)	Rice whiteness ambient air drying	Rice whiteness from fluidized bed drying	Specific electrical energy consumption in terms of primary energy* (MJ/kg-water evap.)	Specific thermal energy consumption (MJ/kg-water evap.)
125	26.8	23.7	62	33.0	32.5	42.4	42.9	0.77	5.47
133	24.1	20.7	63	35.2	37.5	41.5	41.0	0.66	4.69
140	28.0	23.0	64	32.0	37.0	42.5	41.2	0.48	3.80

* Electricity multiplied by 2.6

fluidization technique by Taweerattanapanish *et al.* (1999)

From the test of rice colour of paddy samples dried by ambient air and vibro-fluidized bed dryer, it was found that average rice whiteness were 42.5 and 41.2, respectively (according to scale of whiteness measuring instrument type Kett C-300), with approximately 1.3 difference, as shown in detail in Figure 5.

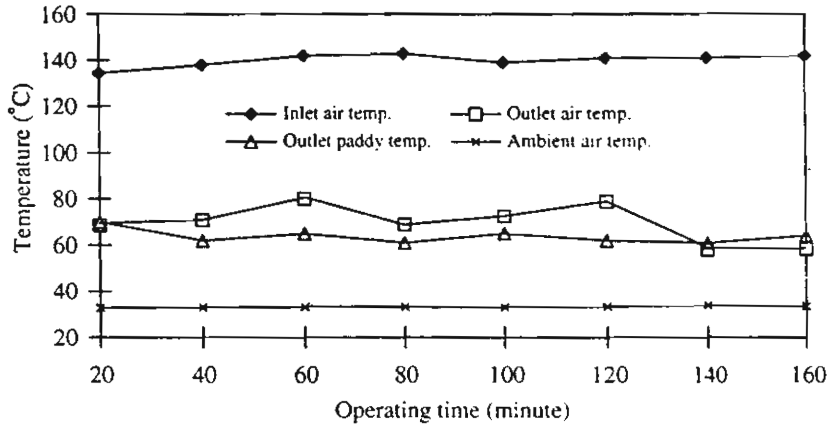

Figure 2 Temperature at various locations.
(average inlet air temperature = 140°C, vibration intensity = 1, feed rate = 1.34 kg/s, inlet moisture content = 28.0 % d.b., bed height = 11.5 cm, bed velocity = 1.4 m/s, outlet moisture content = 23.0 % d.b.)

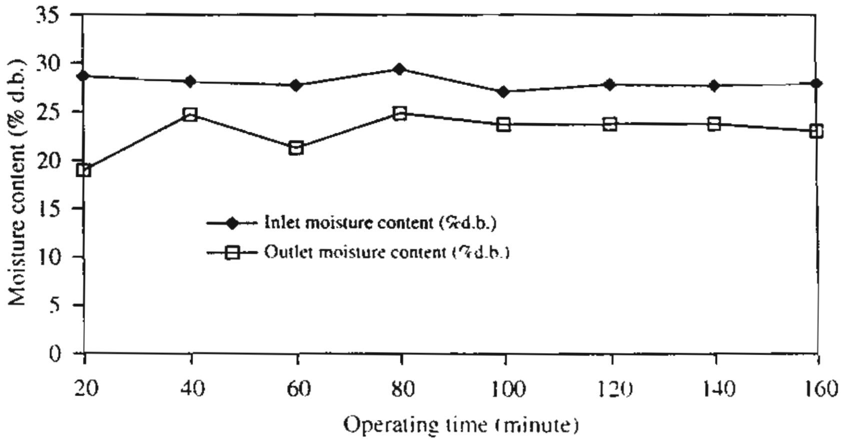

Figure 3 Inlet and outlet moisture content of paddy.
(average inlet air temperature = 140°C, vibration intensity = 1, feed rate = 1.34 kg/s, bed height = 11.5 cm, bed velocity = 1.4 m/s)

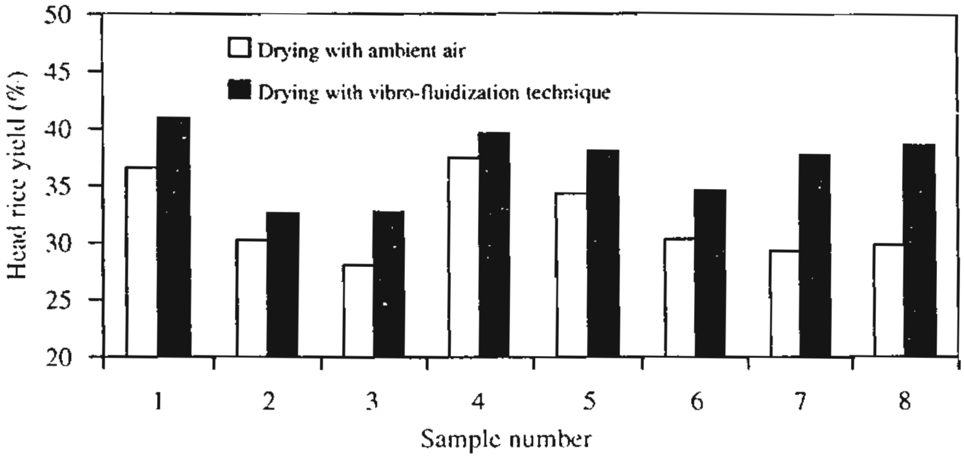

Figure 4 Comparison between head rice yield obtained from vibro-fluidized bed dryer and ambient air drying.
(average inlet air temperature = 140°C, vibration intensity = 1, feed rate = 1.34 kg/s, inlet moisture content = 28.0 % d.b., bed height = 11.5 cm. bed velocity = 1.4 m/s. outlet moisture content = 23.0 % d.b.)

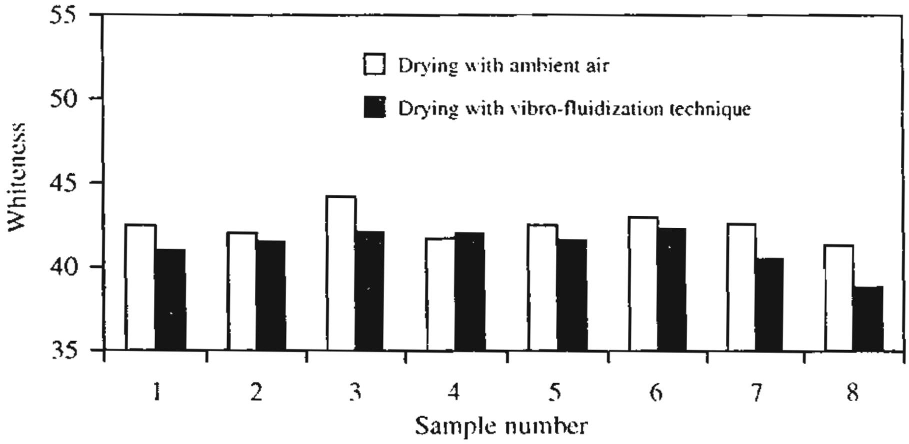

Figure 5 Comparison between rice whiteness obtained from vibro-fluidized bed dryer and ambient air drying.
(average inlet air temperature = 140°C. vibration intensity = 1. feed rate = 1.34 kg/s. inlet moisture content = 28.0 % d.b.. bed height = 11.5 cm. bed velocity = 1.4 m/s. outlet moisture content = 23.0 % d.b.)

Specific energy consumption

In using vibro-fluidized bed dryer, total electrical power consumption was 9,646 W, divided into electrical power consumption of each component as follows:

1. Blower = 55.0 %
2. Vibrator = 10.4 %
3. Rotary feeder = 6.4 %
4. Rotary discharger = 7.1 %
5. Elevator = 13.0 %
6. Burner = 8.1 %

The result from the test of dryer showed that average primary energy consumption was 723.1 MJ/h, of which 87.6, MJ/h was primary energy in terms of electrical energy (multiplied by 2.6) and 635.5 MJ/h was primary energy in terms of thermal energy. Drying rate was 117.6 kg/h. Total average specific primary energy consumption was 6.15 MJ/kg-water evap., nearly the same value as that in case of paddy drying using fluidization technique without vibration. Electrical power of blower motor and vibrator motor was 55 % as compared to electrical power of blower motor used in paddy drying using fluidization technique without vibration Soponronnarit *et al.* (1998).

Cost analysis

The fabrication cost of vibro-fluidized bed dryer was 450,000 baht including labour cost and installing cost (US$ 1 = 40 baht). Salvage value was defined at 10 % of fixed cost. Others costs were based on the results of testing dryer as follows: drying capacity 4.82 tons/h, initial and final moisture contents of paddy 28 and 23 % d.b., respectively. The dryer could evaporate water with a rate of 189.4 kg/h and the operating time of dryer was 90 days/year. The cost analysis was divided into two cases as follows: 1) In case of operating time of dryer 12 hours/day and 2) In case of operating time of dryer 24 hours/day. The results from cost analysis were as follows:

1) In case of operating time of dryer 12 hours/day: The total drying cost was 305,015 baht/year which was divided into fabrication cost 100,131 baht/year. diesel consumption cost 170,726 baht/year, electrical power cost 16,070 baht/year, maintenance cost 20,000 baht/year and salvage value 1,913 baht/year. Therefore, it was found that total drying cost was 59 baht/ton of paddy (1.50 baht/kg-water evap.) of which 19 baht/ton of paddy (0.5 baht/kg-water evap.) was fabrication cost and 40 baht/ton of paddy (1 baht/kg-water evap.) was operating cost.

2) In case of operating time of dryer 24 hours/day: The total drying cost was 49.5 baht/ton of paddy (1.25 baht/kg-water evap.) of which 9.50 baht/ton of paddy (0.25 baht/kg-water evap.) was fabrication cost and 40 baht/ton of paddy (1 baht/kg-water evap.) was operating cost.

CONCLUSION

In this research, a commercial-scale vibro-fluidized bed paddy dryer was tested. The operating conditions were as follows: paddy feed rate 4.82 tons/h, paddy bed height 11.5 cm, drying air flow rate 1.7 m^3/s (1.9 kg/s), drying air velocity through bed 1.4 m/s, fraction of air recycled 0.85 and vibration intensity approximately 1 (frequency 7.3 Hz and amplitude 5 mm). In case of using average inlet air temperature of 140°C, it can be concluded as follows:

1) Vibro-fluidized bed dryer could reduce moisture content of paddy from average 28 % d.b. to 23 % d.b. Paddy temperature at drying chamber outlet was average 64°C.

2) The average percentage of head rice yield of paddy samples dried by ambient air, was 32. For paddy samples dried by vibro-fluidized bed dryer, the average percentage of head rice yield was 37, which was 5 % higher than that dried by ambient air.

3) The rice whiteness of paddy which dried by ambient air and vibro-fluidized bed dryer were approximately 42.5 and 41.2, respectively, according to scale of whiteness measuring instrument type Kett C-300.

4) Total average specific primary energy consumption was 6.15 MJ/kg-water evap.

5) Electrical power of fan motor and vibrator motor was approximately 55 % of the case of drying by fluidization technique without vibration.

6) From drying cost analysis, in case of operating time of dryer 12 hours/day (90 days/year), the total cost of drying was 59 baht/ton of paddy (1.50 baht/kg-water evap.) of which 19 baht/ton of paddy (0.5 baht/kg-water evap.) was fabrication cost and 40 baht/ton of paddy (1 baht/kg-water evap.) was operating cost (US$ 1 = 40 baht).

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เตาเผาแกลบแบบไซโคลน สำหรับการอบแห้งข้าวเปลือก*

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บทคัดย่อ

งานวิจัยนี้มีวัตถุประสงค์เพื่อออกแบบ สร้าง และทดสอบเตาเผาแกลบแบบไซโคลนสำหรับเครื่องอบแห้งข้าวเปลือกแบบฐานก่อสภาพของไหลขนาด ๑๐ ตันต่อชั่วโมง เตาเผาแกลบมีลักษณะเป็นทรงกระบอก เส้นผ่านศูนย์กลาง ๑.๓๗ เมตร สูง ๒.๗๕ เมตร แกลบและอากาศเข้าห้องเผาไหม้ในแนวสัมผัสและเกิดการหมุนในห้องเผาไหม้ จากการทดลองพบว่า ที่ความสูงของเถ้าบนตะแกรงขณะเผาไหม้ ๓๐, ๔๕, ๕๐ และ ๖๐ เซนติเมตร อัตราการป้อนแกลบ ๑๑๐-๑๓๖ กิโลกรัมต่อชั่วโมง อากาศส่วนเกินร้อยละ ๒๖๕-๓๕๐ อุณหภูมิของอากาศเผาไหม้อยู่ในช่วง ๕๒๓-๗๑๐ องศาเซลเซียส ประสิทธิภาพเชิงความร้อนของเตาทั้งระบบเพิ่มขึ้นตามปริมาณอากาศส่วนเกินโดยมีค่าร้อยละ ๕๗-๗๓ ประสิทธิภาพการเผาไหม้คาร์บอนมีค่าร้อยละ ๘๙-๙๗ ความสูงของเถ้าแกลบบนตะแกรงไม่มีผลต่อประสิทธิภาพของระบบ จากการวิเคราะห์ทางเศรษฐศาสตร์ของการใช้เตาเผาแกลบแทนหัวเผาน้ำมันดีเซลพบว่า สามารถคืนทุนได้ภายในระยะเวลา ๑,๒๐๐ ชั่วโมงทำงาน

ABSTRACT : CYCLONIC RICE HUSK FURNACE FOR PADDY DRYING*

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The objectives of this research were to design, construct and test a rice husk furnace for fluidized bed paddy dryer with capacity of 10 tons/h. The furnace was cylindrical in shape with inner diameter of 1.37 m and height of 2.75 m. Air and rice husk entered to combustion chamber in tangential direction with vortex rotation. Experimental results showed that at heights of ash on grate 30, 45, 50 and 60 cm, rice husk feed rates 110-136 kg/h, excess air 265-350 %, combustion gas temperature was approximately 523-710° C. Thermal efficiency of the furnace system which increased with excess air was approximately 57-73 %, while carbon conversion efficiency was approximately 89-97 %. The height of ash on grate had no effect on the system performance. Economic analysis on application of rice husk furnace showed that payback period was 1200 hours when compared to diesel oil burner.

บทนำ

แกลบเป็นเชื้อเพลิงมวลชีวภาพชนิดหนึ่งที่สามารถนำมาใช้เป็นเชื้อเพลิงให้ความร้อนแทนน้ำมัน ซึ่งสามารถลดการนำเข้าน้ำมันจากต่างประเทศได้ ในโรงสีข้าวมีการนำแกลบมาใช้ในระบบหม้อต้มน้ำ ระบบเครื่องกำเนิดไฟฟ้า และระบบการอบแห้ง Singh *et al* [๑] ออกแบบเตาเผาแกลบแบบไซโคลนสำหรับใช้อบแห้งข้าวเปลือกจำนวน ๑ ตัน โดยสามารถลดความชื้นจากร้อยละ ๓๕ มาตรฐานแห้ง เหลือร้อยละ ๑๔ มาตรฐานแห้ง ประสิทธิภาพของเตาขึ้นอยู่กับอัตราการป้อนแกลบและอัตราการไหลของอากาศ เตามีประสิทธิภาพสูงสุดร้อยละ ๘๐ ที่อัตราการป้อนแกลบ ๒๐ กิโลกรัมต่อชั่วโมง และอัตราการไหลของอากาศ ๑๖๘ ลูกบาศก์เมตรต่อชั่วโมง Tumambing[๒] ศึกษาเปรียบเทียบเตาเผาแกลบสำหรับการอบแห้งข้าวเปลือก พบว่าเตาของ Padicor ซึ่งเป็นเตาที่ทำให้แกลบลอยโดยการใช้ลมหมุน มีประสิทธิภาพการเผาไหม้สูงถึงร้อยละ ๙๘ Xuan *et al*[๓] ศึกษาเตาเผา ๒ ชนิดคือ Inclined step-grate และ Vortex type เตาชนิดแรกมีห้องเผาไหม้รูปร่างเป็นกล่องทำด้วยอิฐทนไฟอยู่ทางด้านล่าง ภายในห้องเผาไหม้มีแผ่นตะแกรงเอียงด้านบนเป็นอุปกรณ์แลกเปลี่ยนความร้อนบรรจุภายในถังทรงกระบอก อากาศที่ช่วยในการเผาไหม้ไหลเข้าด้านล่างของตะแกรงและเกิดการเผาไหม้แกลบที่หน้าตะแกรง อากาศร้อนในเตาถูกพัดลมดูดผ่านท่อออกไป เตาชนิดแรกมีประสิทธิภาพร้อยละ ๗๐ อัตราการใช้แกลบ ๒๐-๒๕ กิโลกรัมต่อชั่วโมง เตาชนิดที่ ๒ ประกอบด้วย ๒ ส่วน คือ ห้องเผาไหม้และระบบป้อนแกลบ เตามีรูปร่างทรงกระบอก แกลบไหลเข้าห้องเผาไหม้พร้อมอากาศส่วนแรกในลักษณะเดียวกับไซโคลน แกลบที่เผาไหม้จะตกลงด้านล่าง อากาศร้อนจะลอยขึ้นด้านบน อากาศในท่อลมส่วนที่ ๒ ถูกส่งมาในลักษณะไซโคลนเช่นกัน สามารถ

ดักจับฝุ่นทำให้อากาศร้อนสะอาดขึ้นแล้ว ถูกดูดผ่านท่อออกไปใช้งาน เตาชนิดที่ ๒ มีประสิทธิภาพร้อยละ ๗๕ อัตราการใช้แกลบ ๑๐-๑๒ กิโลกรัมต่อชั่วโมง

จากงานวิจัยที่ผ่านมาสรุปได้ว่า อากาศร้อนจากเตาเผาแกลบแบบไซโคลน สามารถนำมาประยุกต์ใช้เป็นแหล่งให้ความร้อนในกระบวนการต่าง ๆ ได้ ดังนั้น งานวิจัยนี้จึงมีวัตถุประสงค์เพื่อศึกษา ออกแบบ สร้าง และทดสอบเตาเผาแกลบแบบไซโคลน สำหรับใช้ผลิตความร้อนให้กับเครื่องอบแห้งข้าวเปลือกแบบฐานก่อสภาพของไหล (fluidised bed) ขนาด ๑๐ ตันต่อชั่วโมง ที่ได้ทำการผลิตขายทั้งในและต่างประเทศตั้งแต่ พ.ศ. ๒๕๔๐ (Soponronnarit *et al*)[๔]

อุปกรณ์และวิธีการ

ในการออกแบบเตาเผาแกลบแบบไซโคลน เริ่มจากการคำนวณหาความร้อนที่จะต้องให้กับเครื่องอบแห้งแบบฐานก่อสภาพของไหล จากนั้นคำนวณหาอัตราการป้อนแกลบ ในขั้นสุดท้ายคำนวณหาขนาดของห้องเผาไหม้จากสมการที่ (๑)

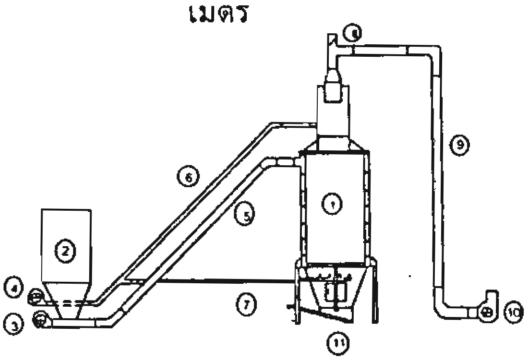
$$V = \frac{B.Q_{wt}}{q_{tr}} \quad (๑)$$

เมื่อ V คือ ปริมาตรห้องเผาไหม้ของเตาเผา, ลูกบาศก์เมตร

B คือ ปริมาณการเผาไหม้เชื้อเพลิงแกลบ, กิโลกรัมต่อชั่วโมง

Q_{wt} คือ ค่าความร้อนของแกลบ, กิโลจูลต่อกิโลกรัม

q_{tr} คือ ภาระความร้อนของเตา, (๕๖๐,๐๐๐-๑,๑๒๐,๐๐๐) กิโลจูลต่อชั่วโมงต่อลูกบาศก์เมตร



รูปที่ ๑ Schematic diagram of rice husk furnace.

เมื่อได้ปริมาตรห้องเผาไหม้แล้วจึงกำหนดมิติของเตาเผา *รูปที่ ๑* แสดงแผนภาพของระบบเตาเผาแกลบแบบไซโคลน ประกอบด้วยอุปกรณ์หลัก ๆ ดังนี้ ห้องเผาไหม้มีลักษณะเป็นโครงเหล็กทรงกระบอก เส้นผ่านศูนย์กลางภายนอก ๑.๗๖ เมตร สูง ๒.๗๕ เมตร หุ้มด้วยฉนวนกันความร้อน ๔ ชั้น ชั้นในสุดเป็นอิฐทนไฟ ชั้นที่ ๒ เป็นแผ่นเหล็ก ชั้นที่ ๓ เป็นใยแก้ว และชั้นนอกสุดเป็นแผ่นเหล็กวางอยู่บนขาตั้งเหล็กรูปตัวไอ (I-Beam) สูงจากพื้น ๑.๔ เมตร ด้านล่างมีตะแกรงขนาดเส้นผ่านศูนย์กลาง ๑.๓๗ เมตร หนา ๙.๕ มิลลิเมตร เจาะช่องขนาดเส้นผ่านศูนย์กลาง ๐.๐๑๒๗ เมตร จำนวน ๕๘๓ ช่องต่อตารางเมตร และมีใบปาดเถ้าทำจากเหล็กหล่อขนาด ๕๐ × ๕๐ มิลลิเมตร

ยาว ๑.๑ เมตร ตรงกลางเจาะช่องใส่เพลา ขนาด ๓๘ มิลลิเมตร ด้านบนห้องเผาไหม้มีทางเข้าของแกลบและอากาศปฐมภูมิ (primary air) เหนือห้องเผาไหม้เป็นโครงเหล็กทรงกระบอก มีเส้นผ่านศูนย์กลางภายในและภายนอก ๐.๘ และ ๐.๘๖ เมตร ตามลำดับ สูง ๑.๖ เมตร หุ้มด้วยฉนวนซีเมนต์ทนไฟและเหล็ก มีทางเข้าของอากาศทุติยภูมิ (secondary air) ด้านล่างห้องเผาไหม้เป็นห้องเก็บเถ้า มีสกรูดึงเถ้าออกโดยใช้มอเตอร์พร้อมเกียร์ทด และมีท่อลมของอากาศส่วนที่ ๓ (tertiary air duct) จ่ายลมเพื่อช่วยในการเผาไหม้ในส่วนของถังบรรจุแกลบ ด้านล่างมีระบบป้อนแกลบขับด้วยมอเตอร์ขนาด ๐.๓๗ กิโลวัตต์ ๑ ตัว พร้อมเกียร์ทดต่ออยู่กับระบบป้อนอากาศปฐมภูมิ ซึ่งประกอบด้วยมอเตอร์พร้อมพัดลม ๑ ชุด ท่อส่งอากาศปฐมภูมิขนาดเส้นผ่านศูนย์กลาง ๐.๑๕๒ เมตร ในส่วนของระบบป้อนอากาศทุติยภูมิ ประกอบด้วย มอเตอร์พร้อมพัดลม ๑ ชุด ท่อส่งอากาศปฐมภูมิขนาดเส้นผ่านศูนย์กลาง ๐.๑๐๒ เมตร มีท่อแยกสำหรับอากาศส่วนที่ ๓ ขนาดเส้นผ่านศูนย์กลาง ๐.๐๗๖ เมตร ท่ออากาศส่วนที่ ๓ แยกออกเป็น ๔ ท่อ เข้าไปใต้ตะแกรง ที่ปลายท่อจะมีช่องสำหรับกระจายลมทางด้านล่างของห้องเผาไหม้ ระบบดูดอากาศออกจากเตาประกอบด้วยพัดลมดูดอากาศขนาด ๑๕ กิโลวัตต์ ๓ เฟส ๑ ชุด ท่อขนาดเส้นผ่านศูนย์กลาง ๐.๒๕๔ เมตร และมีวาล์วปรับปริมาณอากาศเข้ามาผสมอยู่ทางด้านบนของเตา

เครื่องมือวัดข้อมูลมีดังนี้ เครื่องวัดอุณหภูมิ ใช้เทอร์มอคัปเปิลชนิด K ต่อเข้ากับเครื่องเก็บข้อมูล (data logger) ความแม่น ± ๑ องศาเซลเซียส มาตรกระแสไฟฟ้าแบบคล้องสาย (clamp-on meter) ความแม่นร้อยละ ±๐.๕ มาตรความดันของไหล (manometer) ขนาด ๐-๒๐๐ มิลลิเมตรปรอท ความแม่น ± ๐.๑ มิลลิเมตรปรอท มาตรความชื้นสัมพัทธ์ (hygrometer) ขนาด ๐-๑๐๐ % ความแม่นร้อยละ ± ๑ เครื่องชั่งน้ำหนักขนาด ๐-๕๐ กิโลกรัม ความถูกต้อง ±๒๐๐ กรัม เครื่องมือวิเคราะห์สารองค์ประกอบของแก๊สเผาไหม้ คือ O_2, CO, NO_2, SO_2 (ช่วงอุณหภูมิ ๐-๖๐๐ องศาเซลเซียส ความถูกต้อง ± ๓ องศาเซลเซียส, CO ความถูกต้อง ± ๒๐ ppm, O_2 ความถูกต้องร้อยละ ± ๐.๓)

วิธีการทดลองเริ่มจากวัดปริมาณอากาศปฐมภูมิ อากาศทุติยภูมิ และอากาศส่วนที่ ๓ ในท่อ ให้ได้ตามที่กำหนด และชั่งน้ำหนักแกลบที่จะใช้ในการทดลอง จากนั้นป้อนแกลบเข้าไปในเตาให้ได้ความสูงตามต้องการ ใช้น้ำมันเบนซินและกระดาษเป็นตัวจุดเชื้อเพลิงครั้งแรก และเปิดพัดลมหมายเลข ๔ และ ๑๐ เมื่อเวลาผ่านไปประมาณ ๑๐-๑๕ นาที เปิดพัดลมหมายเลข ๓ พร้อมกับเปิดชุดควบคุมการป้อนแกลบและใบปาดโดยตั้งอุณหภูมิชุดควบคุมไว้ที่ ๓๒๕ องศาเซลเซียส ให้เครื่องวัดอุณหภูมิอ่านค่าทุก ๓ นาที และเครื่องวัดปริมาณแก๊สอ่านค่าทุก ๑๐ นาที และอ่านค่าความชื้นสัมพัทธ์ของอากาศโดยใช้มาตรความชื้นสัมพัทธ์อ่านค่า

อุณหภูมิกระเปาะแห้ง กระเปาะเปียก และอุณหภูมิล้อมรอบ เมื่อทำการทดลองตามกำหนดเวลา ให้หยุดระบบป้อนแกลบและปิดพัดลมหมายเลข ๓ และ ๔ ส่วนหมายเลข ๑๐ เปิดไว้ให้ดูดอากาศร้อนในเตาออกให้หมดแล้วจึงปิด ชั่งน้ำหนักเถ้าแกลบ และเก็บตัวอย่างไปวิเคราะห์

ประสิทธิภาพของเตาเผาแกลบ

ประสิทธิภาพของเตาเผาแกลบสามารถคำนวณหาได้จากสมการ

$$\eta_r = \frac{m_a c_p \left(T_2 - T_1 \right)}{m_f \, HHV} \times 100 \qquad (๒)$$

เมื่อ η_r คือ ประสิทธิภาพของเตาเผาแกลบ, ร้อยละ

m_a คือ อัตราการไหลของอากาศ (อากาศที่ใช้ในการเผาไหม้และอากาศที่นำมาผสมกับแก๊สเผาไหม้), กิโลกรัมต่อชั่วโมง

c_p คือ ความจุความร้อนจำเพาะของอากาศ, กิโลจูลต่อกิโลกรัม-เคลวิน

T_1 คือ อุณหภูมิล้อมรอบ, เคลวิน

T_2 คือ อุณหภูมิที่ทางออกของระบบ, เคลวิน

m_f คือ อัตราการป้อนแกลบ, กิโลกรัมต่อชั่วโมง

HHV คือ ค่าความร้อนสูงของเชื้อเพลิงแกลบ, กิโลจูลต่อกิโลกรัม

ประสิทธิภาพการเผาไหม้คาร์บอน (Carbon Conversion Efficiency)

$$\eta_c = \frac{c_h - c_a}{c_h} \times 100 \qquad (๓)$$

ประสิทธิภาพการเผาไหม้คาร์บอนสามารถคำนวณหาได้จากสมการ

เมื่อ η_c คือ ประสิทธิภาพการเผาไหม้คาร์บอน, ร้อยละ

c_a คือ ร้อยละของคาร์บอนในเถ้า × น้ำหนักเถ้า, กิโลกรัม

c_h คือ ร้อยละของคาร์บอนในแกลบ × น้ำหนักแกลบ, กิโลกรัม

ผลและวิจารณ์

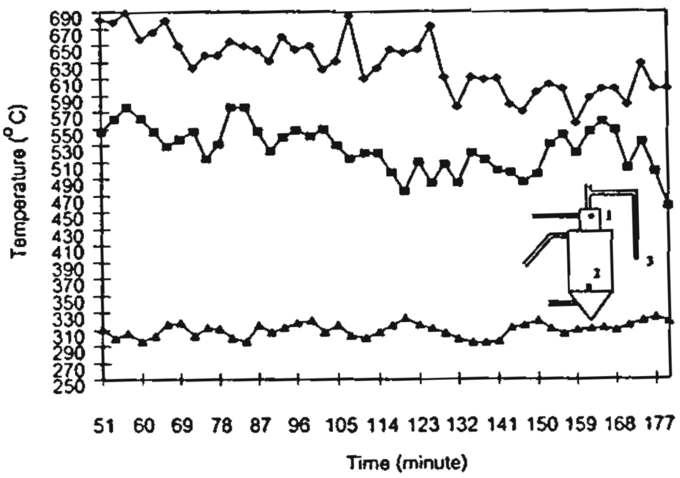
จากการทดลองการเผาไหม้แกลบโดยใช้เตาเผาแบบไซโคลน สามารถแสดงผลแต่ละกรณีได้ดังนี้

การกระจายลมในท่อส่วนที่ ๓

ตารางที่ ๑ และ ๒ แสดงประสิทธิภาพของเตาและการเผาไหม้คาร์บอนที่ความสูงของเถ้าต่าง ๆ กรณีมีท่อกระจายลมด้านล่างตะแกรงจำนวน ๔ ท่อ จากการทดลองที่ ๑/๙๗, ๒/๙๗, ๓/๙๗ และ ๔/๙๗ ที่ความสูงของเถ้าบนตะแกรง ๓๐, ๔๕, ๕๐, ๖๐ เซนติเมตร พบว่าประสิทธิภาพของเตาอยู่ในช่วงร้อยละ ๕๗-๕๙ ประสิทธิภาพการเผาไหม้คาร์บอนมีค่าร้อยละ ๙๓, ๙๕, ๙๖ และ ๙๗ ตามลำดับ ตารางที่ ๔ และ ๕ แสดงประสิทธิภาพของเตาและการเผาไหม้คาร์บอน ที่ความสูงของเถ้าบนตะแกรง ๓๐, ๔๕, ๕๐ และ ๖๐ เซนติเมตร กรณีมีท่อกระจายลมด้านล่างตะแกรงจำนวน ๑ ท่อ จากการทดลองที่ ๑/๙๖, ๒/๙๖, ๓/๙๖, ๔/๙๖ พบว่า ประสิทธิภาพของเตาอยู่ในช่วงร้อยละ ๕๘-๖๓ ประสิทธิภาพการเผาไหม้คาร์บอนมีค่าร้อยละ ๘๘, ๙๓, ๘๕ และ ๙๐ ตามลำดับ สรุปได้ว่า การกระจายลมในท่อส่วนที่ ๓ ไม่ส่งผลกระทบชัดเจนต่อประสิทธิภาพการเผาไหม้คาร์บอนและประสิทธิภาพเตา

อากาศส่วนเกิน

จากผลการทดลอง ดังแสดงในตารางที่ ๑ พบว่า เมื่อใช้อากาศส่วนเกินในการเผาไหม้ร้อยละ ๒๖๐-๒๘๐ (การทดลองที่ ๑/๙๗-๔/๙๗) ประสิทธิภาพของเตาและการเผาไหม้คาร์บอนจะอยู่ในช่วงร้อยละ ๕๘-๕๙ และ ๙๓-๙๗ ตามลำดับ เมื่อเพิ่มปริมาณอากาศส่วนเกินในการเผาไหม้เป็นร้อยละ ๓๔๒-๓๕๐ (การทดลองที่ ๕/๙๗-๗/๙๗) ประสิทธิภาพของเตาและการเผาไหม้คาร์บอนสูงขึ้น เป็นร้อยละ ๗๐-๗๓ และ ๙๕-๙๗ ตามลำดับ อากาศส่วนเกินที่เพิ่มขึ้นมีผลมาจากการลดอัตราการป้อนแกลบ สรุปได้ว่า สภาวะเงื่อนไขการเผาไหม้ที่เหมาะสมที่สุดคือ ความสูงของเถ้า บนตะแกรง ๕๐ เซนติเมตร อัตราการป้อนแกลบ ๑๑๐ กิโลกรัมต่อชั่วโมง อากาศส่วนเกินในการเผาไหม้ร้อยละ ๓๕๐ อุณหภูมิเผาไหม้ในเตาเฉลี่ย ๖๒๘ องศาเซลเซียส มีคาร์บอนที่เหลือในเถ้าร้อยละ ๕.๕ ได้ประสิทธิภาพการเผาไหม้คาร์บอนร้อยละ ๙๖ และประสิทธิภาพของเตาร้อยละ ๗๓ การกระจายอุณหภูมิภายในเตาเผาแกลบที่ความสูงของเถ้าบนตะแกรง ๕๐ เซนติเมตร แสดงในรูปที่ ๒



รูปที่ ๒ Relationship between temperature and time in rice husk furnace at height of ash on grate 50 cm (experiment no. 7/97).

ความสูงของเถ้าบนตะแกรงขณะเผาไหม้

ความสูงของเถ้าบนตะแกรงขณะเผาไหม้ไม่ส่งผลต่อประสิทธิภาพของเตาเผาแกลบมากนัก ดังแสดงในตารางที่ ๔

การเพิ่มอากาศที่ช่วยในการเผาไหม้ในท่อลมส่วนที่ ๓

การเพิ่มอากาศที่ช่วยในการเผาไหม้ในท่อลมส่วนที่ ๓ จากทางด้านล่างมากเกินไป มีผลทำให้การเผาไหม้ไม่สมบูรณ์ เนื่องจากปริมาณอากาศที่เพิ่มขึ้นทำให้เถ้าบางส่วนที่ติดอยู่ที่ช่องตะแกรงหลุดออก ทำให้ช่องตะแกรงมีขนาดใหญ่ขึ้น ส่งผลให้แกลบที่กำลังเผาไหม้อยู่บนตะแกรงตกลงมาด้านล่างก่อนที่จะเผาไหม้หมด ทำให้ปริมาณคาร์บอนที่เหลือจากการเผาไหม้สูงขึ้น ประสิทธิภาพการเผาไหม้คาร์บอนจึงต่ำลง ดังแสดงในตารางที่ ๑ และ ๒ (เปรียบเทียบกันระหว่างการทดลอง ที่ ๖/๔๗ กับ ๑๑/๔๗)

ผลการวิเคราะห์แกลบและเถ้า

ผลที่ได้จากการนำตัวอย่างแกลบและเถ้าในการทดลองเผาไหม้ไปวิเคราะห์ที่กรมวิทยาศาสตร์บริการกระทรวงวิทยาศาสตร์เทคโนโลยีและสิ่งแวดล้อม ได้ผลดังนี้

ผลจากการวิเคราะห์ตัวอย่างแกลบพบว่า มีสารองค์ประกอบทางเคมี คิดเป็นร้อยละโดยมวลดังนี้ ธาตุคาร์บอนร้อยละ ๓๙.๐, ไฮโดรเจนร้อยละ ๕.๔, ออกซิเจนร้อยละ ๔๐.๓, ไนโตรเจนร้อยละ ๐.๑๙, กำมะถันร้อยละ ๐.๐๔, และเถ้าร้อยละ ๑๕.๑ มีความชื้นร้อยละ ๘.๑๐ และค่าความร้อน (calorific value) = ๓,๕๖๖ แคลอรีต่อกรัม

ผลจากการวิเคราะห์เถ้าแกลบจากการทดลองเผาไหม้แต่ละครั้งจำนวน ๑๒ ตัวอย่าง พบว่า มีคาร์บอนที่เหลือจากการเผาไหม้ร้อยละ ๙.๙, ๗.๕, ๕.๙, ๔.๔, ๗.๐, ๔.๙, ๕.๕, ๑๓.๔, ๑๔.๘, ๒๘.๗, ๒๖.๓ และ ๒๒.๘ ตามลำดับ จากผลการวิเคราะห์พบว่า ปริมาณคาร์บอนที่เหลือจากการเผาไหม้สูงขึ้น เนื่องจากการเพิ่มอัตราการไหลของอากาศในท่อลมของอากาศส่วนที่ ๓ ดังแสดงในตารางที่ ๑ เมื่อปริมาณอากาศในท่อสูงขึ้นทำให้แกลบที่กำลังเผาไหม้ตกลงมาด้านล่างของตะแกรง เนื่องจากปริมาณอากาศที่สูงเกินทำให้เถ้าที่เกาะติดอยู่ตามช่องตะแกรงหลุดออก ทำให้ช่องกว้างขึ้น แกลบที่กำลังเผาไหม้อยู่ด้านบนชั้นแกลบถูกหมุนพลิกด้วยใบปาดตกลงมาในขณะที่ยังลุกไหม้ไม่หมด ส่งผลให้มีปริมาณคาร์บอนเหลือจากการเผาไหม้มากขึ้น ทำให้ประสิทธิภาพการเผาไหม้คาร์บอนต่ำลง

ความสิ้นเปลืองพลังงาน

ความสิ้นเปลืองพลังงานไฟฟ้าในอุปกรณ์แต่ละตัวของเตาเผาแกลบมีดังนี้ พัดลมเป่าอากาศปฐมภูมิ ๑.๒๕ กิโลวัตต์ พัดลมเป่าอากาศทุติยภูมิและอากาศส่วนที่ ๓ ๑.๑๘ กิโลวัตต์ พัดลมดูดอากาศออก (suction blower) ๘.๓๖ กิโลวัตต์ มอเตอร์ใบปาดเถ้า ๑.๗๙ กิโลวัตต์ มอเตอร์ระบบป้อนแกลบ ๐.๖๖ กิโลวัตต์ มอเตอร์สกรูดึงเถ้าออก ๐.๗๒ กิโลวัตต์ รวมอัตราการใช้ไฟฟ้าที่ใช้ทั้งหมดเท่ากับ ๑๓.๙๖ กิโลวัตต์ ซึ่งสามารถนำมาเปรียบเทียบกับพลังงาน

ความร้อนที่ได้จากเตาเผา โดยเปรียบเทียบอัตราการใช้ไฟฟ้าในรูปพลังงานปฐมภูมิ ซึ่งมีค่าเท่ากับอัตราการใช้ไฟฟ้าคูณด้วยค่าแฟกเตอร์ ๒.๖ กับพลังงานความร้อนที่ได้จากการเผาไหม้ เมื่อเทียบเป็นร้อยละของความร้อนที่ได้จากเตาเผาพบว่า อัตราการใช้ไฟฟ้าในรูปพลังงานปฐมภูมิมีค่าประมาณร้อยละ ๗ ของอัตราการผลิตความร้อนจากเตาเผาแกลบ ดังแสดงในตารางที่ ๓

การวิเคราะห์ค่าใช้จ่าย

ปัจจุบันเตาเผาแกลบแบบไซโคลนสามารถประยุกต์ใช้งานกับเครื่องอบแห้งแบบฐานก่อสภาพของไหลขนาด ๑๐ ตันต่อชั่วโมงได้โดยมีบริษัทเอกชนผลิตขายไปแล้วกว่า ๒๐ เครื่อง สรายุทธ์ สมิตะโยธิน[๔] ได้ศึกษาและวิเคราะห์ค่าใช้จ่ายในการอบแห้งข้าวเปลือกโดยเครื่องอบแห้งแบบฐานก่อสภาพของไหล กรณีที่นำเตาเผาแกลบแบบไซโคลนมาใช้เป็นแหล่งผลิตความร้อนแทนหัวเผาน้ำมันดีเซล เงื่อนไขในการวิเคราะห์มีดังนี้ ราคาของเครื่องอบแห้งไม่รวมหัวเผาน้ำมันดีเซล ๘๐๐,๐๐๐ บาท ราคาหัวเผาน้ำมันดีเซล ๕๐,๐๐๐ บาท ราคาเตาเผาแกลบแบบ ไซโคลน ๔๐๐,๐๐๐ บาท มูลค่าซากของเครื่องอบแห้งและเตาเผาแกลบร้อยละ ๑๐ ของราคาขาย อายุการใช้งานเครื่องอบแห้ง ๑๐ ปี อายุการใช้งานเตาเผาแกลบ ๕ ปี ค่าบำรุงรักษาเครื่องอบแห้งและเตาเผาแกลบร้อยละ ๕ ของราคาขาย อัตราดอกเบี้ยเงินกู้ร้อยละ ๑๒ ต่อปี ราคาแกลบ ๑๐๐ บาทต่อตัน ราคาเถ้าแกลบ ๑๕๐ บาทต่อตัน ราคาน้ำมันดีเซล ๙.๕๔ บาทต่อลิตร อัตราค่าไฟฟ้า ๑.๗๘ บาทต่อกิโลวัตต์-ชั่วโมง ค่าปรับปรุงต้นทุนการผลิต (Ft) ๐.๓๓ บาทต่อกิโลวัตต์-ชั่วโมง ภาษีมูลค่าเพิ่มร้อยละ ๗ ระยะเวลาการทำงาน ๒,๔๐๐ ชั่วโมงต่อปี อัตราการป้อนแกลบ (กรณีใช้เตาแกลบ) เฉลี่ย ๑๔๒ กิโลกรัมต่อชั่วโมง อัตราการผลิตเถ้าแกลบ ๓๕ กิโลกรัมต่อชั่วโมง อัตราการใช้น้ำมันดีเซล (กรณีใช้หัวเผาน้ำมันดีเซล) ๓๘.๑ ลิตรต่อชั่วโมง ปริมาณการใช้ไฟฟ้าของเครื่องอบแห้งเฉลี่ย ๒๙ กิโลวัตต์ ปริมาณการใช้ไฟฟ้าของเตาเผาแกลบเฉลี่ย ๔ กิโลวัตต์ อัตราการระเหยน้ำเฉลี่ย ๒๙๑ และ ๓๑๖ กิโลกรัมต่อชั่วโมงสำหรับกรณีใช้เตาเผาแกลบและกรณีใช้หัวเผาน้ำมันดีเซลตามลำดับ

จากเงื่อนไขที่กำหนด สามารถคำนวณหาค่าใช้จ่ายในการอบแห้งข้าวเปลือกโดยเครื่องอบแห้งแบบฐานก่อสภาพของไหลที่ใช้เตาเผาแกลบได้ดังนี้ ค่าใช้จ่ายรวม ๐.๘๓ บาทต่อกิโลกรัมน้ำที่ระเหย ค่าเครื่องอบแห้งและเตาเผาแกลบ ๐.๓๘ บาทต่อกิโลกรัมน้ำที่ระเหย ค่าแกลบ ๐.๐๕ บาทต่อกิโลกรัมน้ำที่ระเหย ค่าไฟฟ้า ๐.๒๙ บาทต่อกิโลกรัมน้ำที่ระเหย และค่าบำรุงรักษา ๐.๑๐ บาทต่อกิโลกรัมน้ำที่ระเหย สำหรับการอบแห้งข้าวเปลือกโดยเครื่องอบแห้งแบบฐานก่อสภาพของไหลที่ใช้หัวเผาน้ำมันดีเซล มีค่าใช้จ่ายดังนี้ ค่าใช้จ่ายรวม ๑.๖๑ บาทต่อกิโลกรัมน้ำที่ระเหย ค่าเครื่องอบแห้ง และหัวเผาน้ำมันดีเซล ๐.๑๙ บาทต่อกิโลกรัมน้ำที่ระเหย ค่าน้ำมันดีเซล ๑.๑๗ บาทต่อกิโลกรัมน้ำที่ระเหย ค่าไฟฟ้า ๐.๑๙ บาท ต่อกิโลกรัมน้ำที่ระเหย และ

ค่าบำรุงรักษา ๐.๐๖ บาทต่อกิโลกรัมน้ำที่ระเหย

จากการวิเคราะห์ทางเศรษฐศาสตร์ ระยะเวลาคืนทุนของเตาเผาแกลบแบบไซโคลนเมื่อเปรียบเทียบกับหัวเผาน้ำมันดีเซลพบว่า สามารถคืนทุนได้ภายในระยะเวลา ๑,๒๐๐ ชั่วโมงทำงาน

สรุป

๑. อากาศส่วนเกินที่ใช้ในการเผาไหม้มีผลต่อประสิทธิภาพของเตาเผาแกลบ เมื่ออากาศส่วนเกินเพิ่มขึ้นจากร้อยละ ๒๖๐ เป็นร้อยละ ๓๕๐ ประสิทธิภาพของเตาเพิ่มจากร้อยละ ๕๗ เป็นร้อยละ ๗๓

๒. การกระจายลมในท่อส่วนที่ ๓ มีผลกระทบไม่ชัดเจนต่อประสิทธิภาพการเผาไหม้คาร์บอน และประสิทธิภาพของเตา

๓. ความสูงของเถ้าในช่วง ๐.๓-๐.๖ เมตร ไม่ส่งผลให้ประสิทธิภาพของเตาเผาแกลบเปลี่ยนแปลงมากนัก

๔. อัตราการไหลของอากาศที่ช่วยในการเผาไหม้จากด้านล่างของตะแกรงมีผลต่อประสิทธิภาพการเผาไหม้คาร์บอน ถ้าอัตราการไหลของอากาศสูงจะทำให้แกลบที่กำลังเผาไหม้ตกลงผ่านรูตะแกรงได้เร็วขึ้น ทำให้การเผาไหม้ไม่สมบูรณ์และเหลือปริมาณคาร์บอนในเถ้าสูง

๕. เตาเผาแกลบมีประสิทธิภาพของเตาสูงสุดร้อยละ ๗๓ ที่อากาศส่วนเกินร้อยละ ๓๕๐

๖. จากการวิเคราะห์ค่าใช้จ่ายทางด้านเศรษฐศาสตร์พบว่า เมื่อใช้เตาเผาแกลบแบบไซโคลนเป็นเครื่องผลิตความร้อนแทนหัวเผาน้ำมันดีเซลจะสามารถคืนทุนได้ภายในระยะเวลา ๑,๒๐๐ ชั่วโมงทำงาน

คำขอบคุณ

ผู้เขียนใคร่ขอขอบคุณสำนักงานกองทุนสนับสนุนการวิจัย (สกว.) และ Australian Centre for International Agricultural Research ที่สนับสนุนการวิจัย ขอขอบคุณบริษัทไรซ์เอ็นจิเนียริ่งซัพพลาย จำกัด ที่ช่วยจัดสร้างต้นแบบเตาเผาแกลบแบบไซโคลน และเจ้าหน้าที่กองเกษตรวิศวกรรมทุกท่าน ที่ให้ความช่วยเหลือในด้านสถานที่และคำแนะนำ.

Table 1 Efficiency of rice husk furnace (experiment in 1997).

Experiment no.	Height of ash (cm)	Feed rate of rice husk (kg/h)	Air flow rate for combustion (kg/s)	Air flow rate in primary duct (Ø = 0.152 m) (kg/s)	Air flow rate in secondary duct (Ø = 0.102 m) (kg/s)	Air flow rate in tertiary duct (Ø = 0.076 m) (kg/s)	Excess air (%)	Ambient air temperature (°C)	Temperature in furnace (°C)	Exit air Temperature* (°C)	Efficiency of furnace (%)
1/97	30	135	0.627	0.400	0.178	0.048	265	34	531	304	58
2/97	45	133	0.627	0.400	0.178	0.048	270	34	530	302	58
3/97	50	136	0.625	0.398	0.178	0.048	260	35	523	304	57
4/97	60	130	0.628	0.401	0.179	0.048	280	33	554	301	59
5/97	30	110	0.628	0.401	0.179	0.048	350	33	571	299	70
6/97	45	112	0.628	0.401	0.179	0.048	342	33	568	306	70
7/97	50	110	0.626	0.400	0.178	0.048	350	34	628	310	73
8/97	50	111	0.621	0.400	0.161	0.060 **	342	34	710	311	72
9/97	50	125	0.619	0.400	0.149	0.070 **	294	34	598	301	62
10/97	30	133	0.676	0.398	0.178	0.099 **	299	35	502	297	57
11/97	45	125	0.674	0.397	0.177	0.099 **	323	36	566	297	60
12/97	50	136	0.674	0.397	0.177	0.099 **	289	36	527	295	54

* Mixed air between combustion air and ambient air

** Increasing air flow rate in tertiary duct

Table 2 Carbon conversion efficiency of rice husk furnace (experiment in 1997).

Experiment no	Carbon in rice husk (%)	Carbon in ash (%)	Rice husk consumption (kg)	Ash (kg)	CO value (ppm)	O_2 value (%)	Carbon conversion efficiency obtained from carbon balance (%)	Carbon conversion efficiency measured (%)
1/97	39	9.9	318	84	1025-1869	17.4-18.6	93	93
2/97	39	7.5	288	70	1129-1999	17.2-18.7	93	95
3/97	39	5.9	320	75	142-1732	17.4-18.4	94	96
4/97	39	4.4	254	60	1083-1982	17.0-19.1	95	97
5/97	39	7.0	259	62	1253-1946	17.9-18.9	96	95
6/97	39	4.9	253	60	1204-1832	17.4-18.4	98	97
7/97	39	5.5	237	53	200-1803	17.4-18.4	96	96
8/97	39	13.4	250	58	1200-1993	17.4-18.4	90	92
9/97	39	14.8	262	74	1232-1879	17.5-18.6	87	89
10/97	39	28.7	320	83	1230-1896	17.4-18.4	81	81
11/97	39	26.3	289	74	1235-1999	17.4-19.0	83	82
12/97	39	22.8	320	79	1260-1988	17.2-18.7	85	85

- Low values of NO_2 and SO_2 (NO_2 : 1-12 ppm, SO_2 1-20 ppm)

Table 3 Electricity consumption (experiment in 1997).

Experiment no.	Feed rate of rice husk (kg/h)	Electricity consumption rate (kW)	Electricity consumption rate in terms of primary energy* (kW)	Heat production rate of rice husk furnace (kW)
1/97	135	13.96	36.30	559.68
2/97	133	13.96	36.30	551.40
3/97	136	13.96	36.30	563.83
4/97	130	13.96	36.30	538.95
5/97	110	13.96	36.30	456.04
6/97	112	13.96	36.30	464.33
7/97	110	13.96	36.30	456.04
8/97	111	13.96	36.30	460.20
9/97	125	13.96	36.30	518.23
10/97	133	13.96	36.30	551:40
11/97	125	13.96	36.30	518.23
12/97	136	13.96	36.30	563.83

* Multiple by factor 2.6

Table 4 Efficiency of rice husk furnace at various height of ash (experiment in 1996).

Experiment no.	Height of ash (cm)	Feed rate of rice husk (kg/h)	Air flow rate for combustion (kg/s)	Air flow rate in primary duct (Ø=0.152 m) (kg/s)	Air flow rate in secondary duct (Ø=0.102 m) (kg/s)	Air flow rate in tertiary duct (Ø=0.051 m) (kg/s)	Excess air (%)	Ambient air temperature (°C)	Exit air temperature (°C)	Furnace efficiency (%)
1/96	30	127	0.626	0.400	0.178	0.048	287	34	294	62
2/96	45	133	0.626	0.400	0.178	0.048	269	34	296	59
3/96	50	126	0.628	0.401	0.179	0.048	290	33	296	63
4/96	60	143	0.631	0.402	0.180	0.049	245	32	297	58

Table 5 Carbon conversion efficiency of rice husk furnace at various height of ash (experiment in 1996).

Experiment no.	Height of ash (cm)	Carbon in rice husk (%)	Carbon in ash (%)	Rice husk Consumption (kg)	Ash (kg)	CO value (ppm)	O_2 value (%)	Carbon conversion efficiency obtained from carbon balance (%)	Carbon conversion efficiency measured (%)
1/96	30	36.8	19.3	381	101.0	1300-1600	18	87	88
2/96	45	36.8	12.6	399	93.0	1700-1800	18	95	93
3/96	50	36.8	24.8	378	102.5	1600-1900	18	83	85
4/96	60	36.8	14.9	429	108.0	1000-1800	18	94	90

- Low values of NO_2 and SO_2 (NO_2 : 30-60 ppm, SO_2 3 -20 ppm)

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๕. สรายุทธ์ สมิตะโยธิน. การทดสอบเปรียบเทียบการอบแห้งข้าวเปลือกโดยเทคนิคฟลูอิไดเซชันที่ใช้ความร้อนจากเตาเผาแกลบและหัวเผาน้ำมันดีเซล, วิทยานิพนธ์ปริญญาวิศวกรรมศาสตรมหาบัณฑิต สาขาวิชาเทคโนโลยีการจัดการพลังงาน มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี, ๒๕๔๒.

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Parameters for Mango Glace´ Drying Simulation

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ABSTRACT

The objective of this research was to investigate parameters affecting drying rate of mango glace´, *i.e.*, diffusion coefficient, equilibrium moisture content, specific heat and density of mango glace´. The equilibrium moisture content was determined by static method at temperature of 45-70°C and relative humidity of 10-90%. Saturated salt solutions and an oven were used for controlling relative humidity and temperature, respectively. It was found that equilibrium moisture content decreased with temperature for relative humidity ranging from 10-60%. The BET equation was found accurate to describe the experimental results. The results obtained from drying experiment indicated that diffusion coefficient increased exponentially with drying temperature. It was further found that density and specific heat of mango glace´ decreased and increased linearly with moisture content, respectively.
Key words: BET equation, diffusion coefficient, fruit drying, mango glace´, saturated salt

INTRODUCTION

At present, there are many kinds of fruit in Thailand, which are high requirement for both domestic and export markets. However, there is still problem about fruit storage. Fruit drying is an important approach for solving the problem, as dried fruit can be stored in warehouse for long time. Fruit drying analysis is an important method to determine the suitable conditions for reducing drying cost and maintaining product qualities.

Achariyaviriya and Soponronnarit (1990) studied drying parameters and developed mathematical model of papaya glace´ drying. It was found that BET equation (Brunauer *et al.* 1938) was accurate to describe the experimental results of equilibrium moisture content of papaya glace´. A mathematical equation used for predicting diffusion coefficient was accurate to describe at temperature ranging from 40-80°C. From the experimental results of density and specific heat of papaya glace´, it was found that both of these increased linearly with moisture content. Nuimeem *et al.* (1993) studied the optimum strategy for pineapple glace´ drying. It was found that the appropriate operating parameters were as follows: drying air temperature of approximately 65°C, specific air flow rate of 11 kg-dry air/h kg-dry pineapple glace´ and air recycle of approximately of 75%. The product quality was good and energy consumption reduced. Teanchai and Soponronnarit (1991) studied parameters to evaluate and analyse pineapple glace´ drying. It was found that Iglesias equation (Iglesias *et al.*, 1975) could describe in

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accordance with experimental results of equilibrium moisture content of pineapple glace´. The experimental conditions were as follows: drying temperature of 45-70°C and moisture content of 10-80% dry basis. It indicated that diffusion coefficient increased exponentially with drying temperature. It was further found that density and specific heat of pineapple glace´ increased linearly with moisture content.

All fundamental properties such as equilibrium moisture content, diffusion coefficient, specific heat and densities of mango glace´ were therefore to investigate and determine in order to use for the mango glace´ drying simulation.

MATERIALS AND METHODS

To determine equilibrium moisture content of mango glace´, the samples were cut into thin pieces (thickness about 2-3 mm) and placed on wire net hanging in five bottles which contained saturated salt solution of KNO_3, NaCl, $Mg(NO_3)_2.6H_2O$, $MgCl_2.6H_2O$ and LiCl. After that, placed the five bottles of samples in an oven. The experimental conditions were as follows: oven temperature of 45-70°C and testing time was approximately 14 days. Finally, took the samples out of bottles to determine equilibrium moisture content.

To determine diffusion coefficient of mango glace´, the samples were cut into dimension of $1\times1\times0.5$ cm^3 and placed in a dryer which drying temperature and air flow rate could be controlled. The experimental conditions were as follows: drying temperature of 45-70°C, drying air velocity of 0.6 m/s and moisture content after drying was approximately 15% dry basis.

To determine specific heat of mango glace´, the samples were cut into thin pieces (thickness about of 3 - 4 mm). Measured the specific heat by calorimeter at moisture content of 10-60% dry basis.

To determine density of mango glace´, the samples were cut into small rectangular pieces. Weighed the samples and measured the dimension by a vernier to calculate volume and density. The moisture content of mango glace´ in this experiment was in range of 10-50% dry basis.

To determine moisture content of mango glace´, the samples were placed in an oven at constant temperature of 103°C for 72 hours. The temperature was measured by K-type thermocouple, connected to a data logger with an accuracy of ± 1° C.

RESULTS AND DISCUSSION

The BET equation (Brunauer *et al.*, 1938) was employed for the regression analysis. It is written as follows:

$$RH/(1-RH)M_{eq} = 1/M_mC + [(C-1)/(M_mC)]RH \quad (1)$$

Where RH = relative air humidity, fraction
M_{eq} = equilibrium moisture content of mango glace´, % dry basis

M_m and C were depended on drying air temperature (T) as follows:

M_m = 21.443 exp (-0.015175T)
C = 6738.6 exp (-0.13443T)

It was found that the BET equation could describe in accordance with experimental results, as shown in Figure 1. From the study on the effect of air temperature and relative humidity on equilibrium moisture content of mango glace´ as shown in Figure 2, it was found that if air temperature increased, equilibrium moisture content decreased at relative humidity from 10-60%. It was because when air temperature increased, vapour pressure of mango glace´ increased, causing equilibrium moisture content decrease. On the other hand, when relative humidity was higher than 60%, equilibrium moisture content increased. At higher range of relative humidity, the effect of sugar content was more significant. The vapour was absorbed more. Figure 3 shows the comparison among equilibrium moisture content of mango glace´ with sugar concentration of 60°Brix, papaya glace´(Achariyaviriya and Soponronnarit, 1990) and pineapple glace´ (Teanchai and Soporonnarit, 1991) with sugar concentration of 70°Brix. The BET equation was used to calculate equilibrium moisture contents of these fruit glace´. It was found that at air temperature of 45-70°C, equilibrium moisture isotherm lines of mango and papaya glace´ were nearly the same values, but those of mango and pineapple glace´ were different. It was because the internal structures of each kind of fruit were different.

From the experiment on the diffusion coefficient of mango glace´ at air temperature of 45-70°C, the regression equation technique was used to analyze experimental results. It was found that the relationship between diffusion coefficient and drying air temperature could be written as follows:

$$D = 5.2148\times10^{-10} \exp(0.079062T) \quad (2)$$

where D = diffusion coefficient of mango glace´, m^2/h

T = drying air temperature, °C

Figure 4 shows the comparison of diffusion coefficient of experimental and simulated results at various temperatures. It was found that the diffusion coefficient varied with air temperature. It was because when air temperature increased, the difference of internal and external vapour pressures also increased, causing moving rate of water from inside to the surface of mango glace´ increase.

Figure 5 shows the comparison of the diffusion coefficient of mango glace´ with sugar concentration of 60°Brix, papaya glace´ (Achariyaviriya and Soponronnarit, 1990) and pineapple glace´ (Teanchai and Soporonnarit, 1991) with sugar concentration of 70°Brix. It was found that the best moisture diffusion of the three fruit types at the same air temperature was pineapple, papaya, and mango glace´, respectively. It was because the internal structure of pineapple glace´ was more porous than those of mango and papaya glace´.

Figure 6 shows the mango glace´ densities at various moisture contents. It was found that density decreased linearly with increasing of moisture content. Using least square regression technique to determine the relationship between density and moisture content of mango glace´, the following equation was found.

$$\rho = 1419.8 - 3.8057M \quad (3)$$

where ρ = density of mango glace´, kg/m^3

M = moisture content of mango glace´, % dry basis

Figure 7 shows the comparison of the densities of mango glace´(sugar concentration of 60°Brix), papaya glace´(Achariyaviriya and Soponronnarit, 1990) and pineapple glace´ (Teanchai and Soporonnarit, 1991) at various moisture contents. The sugar concentration of the last two fruits was 70°Brix. It was found that when moisture content increased, density of mango glace´ decreased, but densities of papaya and pineapple glace´ increased. It was because the internal structure of mango glace´ had higher shrinkage than those of papaya and pineapple glace´.

Figure 8 shows the relationship between specific heat and moisture content of mango glace´.

It was found that specific heat increased linearly with moisture content. Least square regression technique was used to determine the relationship between specific heat and moisture content of mango glace´. The relation equation can be expressed as below:

$$C_S = 2.23 + 0.0205M \quad (4)$$

Where C_S = Specific heat of mango glace´, kJ/kg°C

M = Moisture content of mango glace´, % dry basis

Figure 9 shows the comparison of specific heat of mango glace´ (sugar concentration of 60° Brix) and pineapple glace´ (Teanchai and Soporonnarit, 1991) at various moisture contents. The sugar concentration of pineapple glace´ was 70°Brix. It was found that specific heats of these fruits varied linearly with moisture content. At moisture content ranging from 0-70% dry basis, specific heat of mango glace´ was higher than that of pineapple glace´.

CONCLUSION

From the experimental results and discussion, it can be concluded as follows:

1. The BET equation was found accurate to describe the experimental results of equilibrium moisture isotherm at air temperature of 45-70°C and relative humidity of 10-90%. From the experimental results, it was found that equilibrium moisture content of mango glace´ decreased with air temperature at relative humidity ranging from 10-60%. The comparison of equilibrium moisture contents of mango, papaya and pineapple glace´ showed that the equilibrium moisture isotherms of mango and papaya glace´ were nearly the same.

2. Mathematical equation developed to

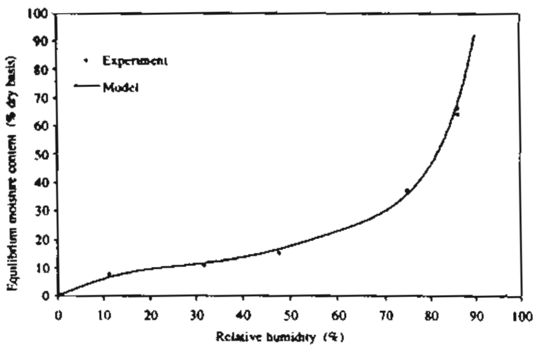

Figure 1 Comparison of predicted values of BET equation with the experimental data at air temperature of 45°C.

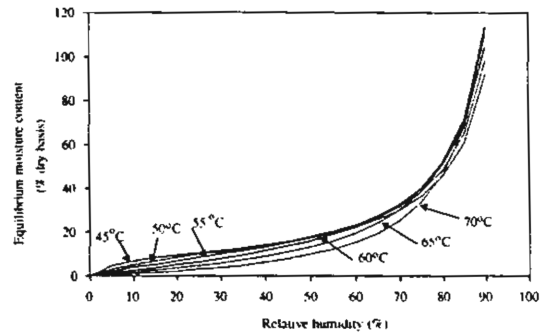

Figure 2 Relationship between equilibrium moisture content and relative humidity of BET equation at various temperatures.

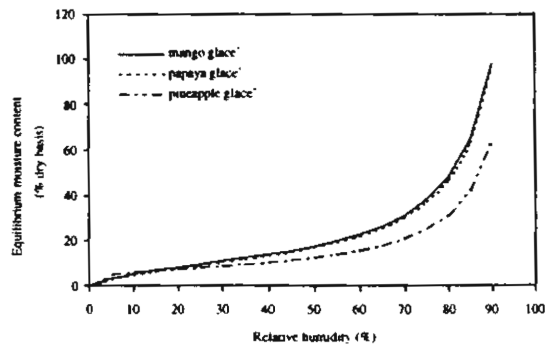

Figure 3 Comparison of equilibrium moisture content of fruit glace´ at air temperature of 50°C.

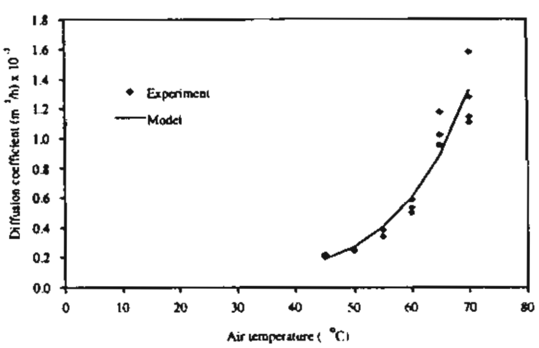

Figure 4 Relationship between diffusion coefficient and air temperature.

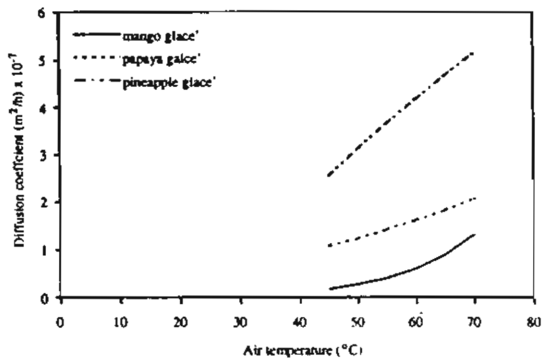

Figure 5 Comparison of diffusion coefficient of fruit glace'at various air temperatures.

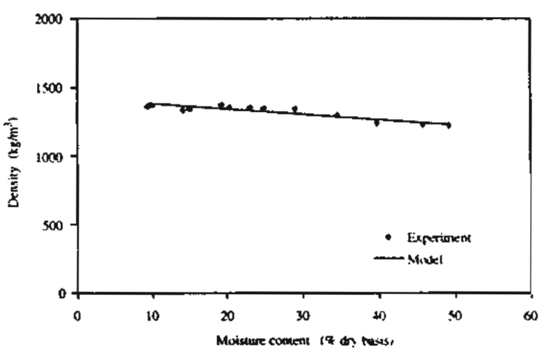

Figure 6 Relationship between density and moisture content of mango glace'.

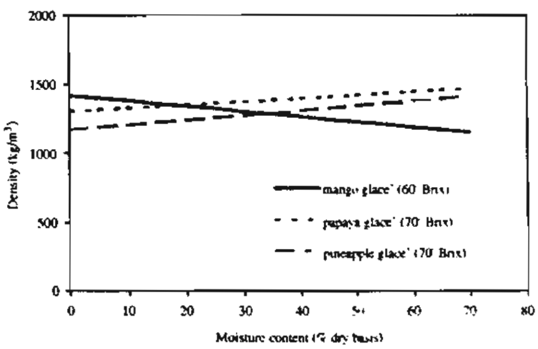

Figure 7 Comparison of density of fruit glace'at various moisture contents.

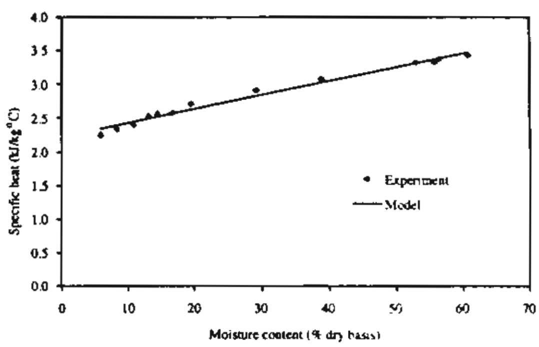

Figure 8 Relationship between specific heat and moisture content of mango glace'.

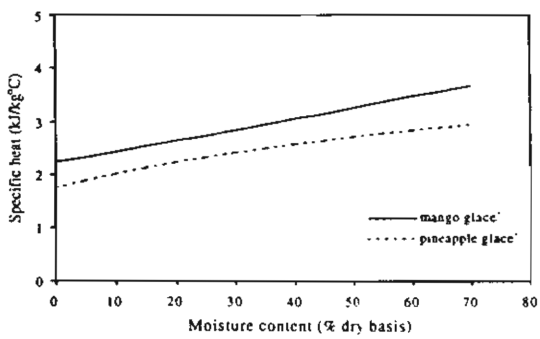

Figure 9 Comparison of specific heat of fruit glace'at various moisture contents.

predict the diffusion coefficient of mango glace´ was good prediction with air temperature ranging from 45-70°C. From the experimental results, it was found that diffusion coefficient increased exponentially with air temperature. The best moisture diffusion of the three fruit glace´ types was mango glace´, papaya glace´ and pineapple glace´, respectively.

3. Mathematical equation developed to predict the density of mango glace´ was good prediction at all of moisture content levels. From the experimental results, it was found that when moisture content increased, density of mango glace´decreased, but densities of papaya and pineapple glace´ increased.

4. Mathematical equation developed to predict the specific heat of mango glace´ was good prediction at all of moisture content levels. It was further found that at moisture content range of 0-70% dry basis, specific heat of mango glace´ is higher than that of pineapple glace´.

ACKNOWLEDGEMENT

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Drying of High Moisture Paddy by Two-Dimensional Spouted Bed Technique

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ABSTRACT

The objectives of this research were to design and construct a two-dimensional spouted bed dryer with draft plates, to study drying kinetics of paddy, paddy quality and specific primary energy consumption. Experimental drying conditions were as follows: initial paddy moisture contents (M_i) of 31.1-45.6% dry basis (d.b.), inlet air temperatures (T_i) of 130, 140 and 150°C, hold-ups (H) of 20, 25 and 30 kg. Experimental results showed that minimum spouting velocity of drying air at the inlet of drying chamber was 15.4-16.4 m/s equivalent to velocity through the draft plates of 3.9-4.1 m/s. The operating parameters affecting drying rate and specific primary energy consumption were drying temperature and specific air flow rate or hold-up. Those affecting head rice yield and rice whiteness were initial and final moisture contents of paddy and drying air temperature. The entrance height directly affected energy consumption of the fan. The suitable entrance height was 10 cm as it resulted in minimum energy consumption. The first order polynomial equation was accurate and appropriate for predicting drying rate.

Key words: dehydration, drying equation, paddy, spouted bed

INTRODUCTION

Most agricultural grains usually harvested at moisture levels more than 25% dry basis (d.b.) need to be dried to an acceptable moisture level for safe storage over long periods. Grain normally has an irregular shape and large size so that a conventional fluidized bed often shows a slugging bed for such coarse grain, thus resulting in poor solid-air mixing and inefficient heat utilisation for evaporating moisture from grains. However, good solid mixing and effective gas-solid contact can be smoothly achieved by the spouted bed technique.

So far, this approach provides lower pressure drop across the bed and can be applied effectively for heat-sensitive materials in particular agricultural and phanological products, since the increase of particle temperature is obtained by thoroughly mixing and short contact time in spout region. As high as possible for inlet air temperature, depending upon the degradation temperature of particular product, can therefore be used for drying. The use of high drying air temperature may enhance the thermal efficiency and drying capacity and reduce the dryer size.

Mathur and Epstein (1974) studied grain drying using spouted bed technique. In their work, the conical-cylindrical vessel with a centrally lo-

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cated small opening of inlet air was used. The high air velocity transports and accelerates the grains and carries them upward through spout zone in which heat and mass transfers are essentially intense. After reaching a certain bed height over the bed surface, which is a so-called fountain, grains reduce to their terminal velocity, separate from the air stream and fall into the annulus region between the jet zone and the vessel wall. The annulus region is a dense phase where the particles and drying air move in counter-current flow. Particle mixing is very strong at the bottom of annulus due to its movement to entrain into spout. Having a cyclic pattern and the spout are the main characteristic of this dryer type. However, this conventional spouted bed had disadvantages as follows: higher pressure drops as compared to the fluidized bed and limitations for increasing drying capacity in commercial scale. In order to improve it, the draft tubes were inserted in the central region of the vessel which separated the zones between spout and annulus. Such technique therefore gives more stable solid circulation and reduction of bed pressure drop while it still maintains the important feature of stable spout (Viswanathan *et al.*, 1986).

As previously mentioned important characteristics of spouted bed, the study of drying characteristic has been received much attention in the literatures (Viswanathan *et al.*, 1986, Zahed and Epstein, 1992, Kalwar and Raghavan, 1993 and Tulasidas *et al.*, 1993) whilst the product quality testing after drying has been received less attention in the literature although it is very important.

In this work, a two-dimensional spouted bed with draft plates acting in a similar manner to that proposed by Tulasidas *et al.*(1993) was constructed and used to investigate the relationship of operating parameters to the drying rate and the energy consumption. In addition, the paddy qualities in terms of rice whiteness and head rice yield were considered. This paper is organised as follows. The details of dimensions of the two-dimensional spouted bed dryer, the experimental conditions and the method of quality testing are first given in the materials and method section. Then, the paddy phenomenon while spouting and the pressure drop behaviour related to the air flow rate are given in details. Eventually, the drying kinetics, energy consumption and paddy qualities are discussed.

MATERIALS AND METHODS

Materials

In this experiment, a two-dimensional spouted bed dryer with draft plates as shown in Figure 1 was used. The inlet cross section area was 4×15 cm^2, drying chamber $60\times15\times150$ cm, width of spout (w_d) 8 cm and entrance height 10 cm. A 15 kW electric heater was installed at the ambient air inlet, temperature controlled by an on-off temperature controller (thermostat). The fan used was a backward-curved blade centrifugal fan driven by a 2.2 kW motor, directly connected to a variable speed controller.

In order to get rid of the dead zone, the slanted base was fixed at an angle of 60° recommended by Passos *et al.*(1987). Kalwar *et al.* (1991) found a dominant dead region at the bottom for slant angle lower than 30°. The deflector was designed for limiting the spout height and for entrapping the entrainment of the paddy. Consequently, the grain particles drop into the downcomer zone. The front cover was made of the heat resistant glass to visualise the paddy behaviour during drying.

The selected values of spout width and entrance height as above mentioned were appropriate for maintaining the paddy transport to the draft channel and the stable spouting behaviour. From the preliminary testing, it showed that the plugging of paddy at the draft channel occurs when the spout width becomes lower than 8 cm. For the entrance height, the pressure drop greatly increases with increase of entrance height and hence, it is more difficult to sustain the spouting behaviour in the draft channel due to limitation of the fan power used in this experiment. It is therefore fixed at the value of

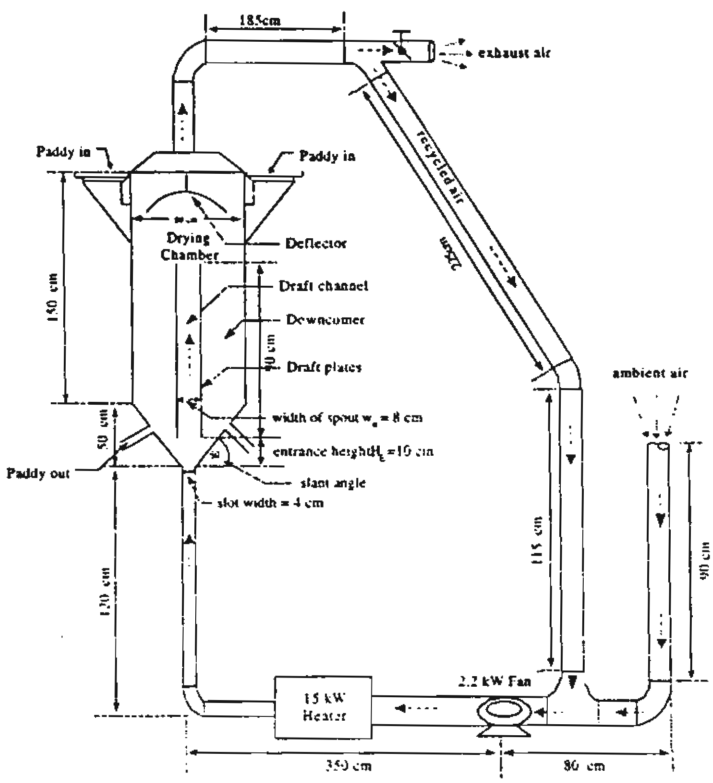

Figure 1 Diagram of the experimental two-dimensional spouted bed dryer.

10 cm.

Drying air and paddy temperatures were measured by the k-type thermocouples connected to a data logger with an accuracy of ±1°C. The temperature at downcomer was measured at levels 10, 30, 50 and 70 cm. Pressure drop across the bed and inlet air velocity were measured by a U-tube manometer and a hot wire anemometer with an accuracy of ±4%, respectively. To determine moisture content, samples were taken at five minutes intervals for periods of 5-20 minutes during the experiment and dried in a hot air oven at a temperature of 103°C for 72 h.

Experiments

1. Preparation of moist paddy and drying conditions

Moist paddy was prepared by uniformly spraying water on paddy, mixed throughly, kept in a closed lid bin and stored in a cold room at temperature approximately 8-10°C for 5-7 days in order to avoid the moisture gradients inside the paddy kernel.

Experimental drying conditions were as follows: initial moisture contents (M_i) of 31.1, 37.8 and 45.6% d.b., bed hold-ups (H) of 20, 25 and 30 kg corresponding to bed heights (H_b) of 40, 50, and 60 cm, respectively, drying air temperatures at drying chamber inlet (T_i) of 130, 140 and 150°C.

2. Determination of pressure drop and minimum spouting velocity

Various initial moisture contents of paddy (M_i) between 31.1 and 45.6% d.b.and some amounts of paddy (H) 20, 25 and 30 kg were used. A low ambient air flow rate was initially flowed through the drying chamber and the pressure drop across the dryer was then measured. These processes were repeated by increasing continuously airflow rate until the pressure drop ultimately approached to a constant value at which paddy entrains out of the draft channel.

3. Drying experiments and paddy quality testing

For testing the paddy quality, moist paddy dried to different moisture levels at spouted bed dryer was then dried with ambient air until the moisture reduces to 16% d.b. Finally, the dried paddy was passed through the milling process to quantitatively determine head rice yield and rice whiteness. The head rice yield, defined as the rice having the long size at least 8/10 of the whole rice, was determined according to the method of the Rice Research Institute (Pathum Thani) and the rice whiteness was measured by using a Kett meter C-300. In order to consider the impacts of the final moisture content (M_f) and the drying temperature on such both qualities, the paddy used as a reference was dried carefully with air at room. For better comparison, both head rice yield and rice whiteness were reported in terms of relative values as follows:

Percentage of relative head rice yield =

$$\frac{\text{rice yield of paddy dried by spouted bed dryer}}{\text{rice yield of paddy dried by ambient air}} \times 100 \qquad (1)$$

Percentage of relative rice whiteness =

$$\frac{\text{head rice whiteness of paddy dried by spouted bed dryer}}{\text{head rice whiteness of paddy dried by ambient air}} \times 100 \qquad (2)$$

RESULTS AND DISCUSSION

1. Pressure drop and minimum spouting velocity

From varying initial moisture contents (M_i) between 31.1 and 45.6% d.b. and hold-ups (H)between 20 and 30 kg corresponding to the bed heights between 40 and 60 cm, respectively. It was found that when the air velocity between draft plates is so high enough that the paddy existing between draft plates is started moving, the pressure drop at this point had a maximum value. As the air velocity is further increase, the pressure drop would decrease and ultimately approached to a constant value although the air velocity increased. The first point of inlet air velocity at which the pressure drop is independent to air speed is a so-called minimum spouting velocity. As shown in Figure 2, the minimum spouting velocity increased linearly with the bed height and the values were in a range of 15.6 - 16.4 m/s, at 4 cm-wide dryer-inlet with width of spout 8 cm and entrance height 10 cm, equivalent to the air velocity flowing through the draft plates of 3.9 and 4.1 m/s, respectively. The pressure drops at minimum spouting velocity varied from 1400 Pa for bed hold-up of 20 kg to 2300 Pa for bed hold-up of 30 kg. The maximum pressure drop at initial movement of paddy was range of 2000 Pa for 20 kg bed hold-up and 3600 Pa for 30 kg bed hold-up.

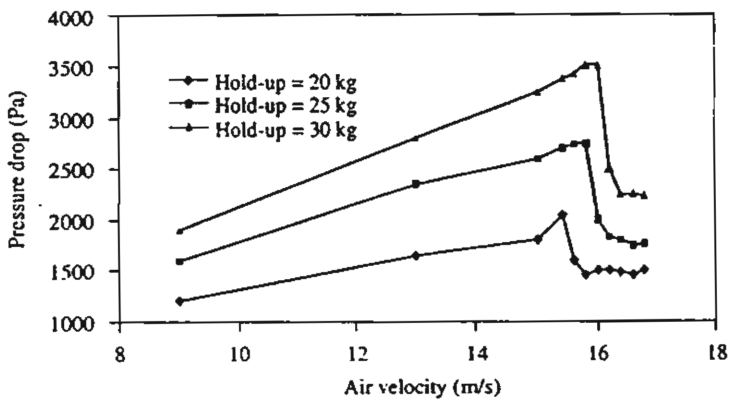

Figure 2 Relationship between pressure drop and air velocity (at the dryer inlet) at different hold-ups. (M_i = 31.1% d.b.)

In contrast, the minimum spouting velocity was independent to the moisture content in the range considered. The explanation of such variations of the minimum spouting velocity links intimately with the pressure in that higher pressure drops, due to larger amounts of solid existing at spout region, result from increase of bed height (H_b). Therefore, higher air velocity would be needed to obtain a stable spouting.

2. Influence of parameters on the moisture contents

The effect of specific air flow rate on diffusion rate of paddy by representing in terms of moisture content ratio (MR) at different specific air flow rate as shown in Figure 3 for inlet air temperature 150°C. The moisture ratio is defined as $(M_t-M_{eq})/(M_{in}-M_{eq})$ where M_{eq} is equilibrium moisture content of paddy which was calculated by Henderson equation (1952). M_i is initial moisture content and M_t is moisture content at time t. The specific air flow rate is defined as the total mass flow rate of inlet air divided by the total mass of paddy with free moisture. As shown in Figure 3, the moisture content of paddy is reduced linearly with drying time. In addition, it varied with specific air flow rates; higher specific air flow rates provided significantly faster moisture extraction rates than lower specific air flow rates under the same drying time. This is caused by the fact that the increased air flow rate resulted further in more circulation of paddy being transported through the central channel or shorter time for grain relaxation in the downcomer and hence, the paddy was more often contacted with the existing high temperature, resulting in greater amounts of their moisture diffused from the inside to the paddy surface and then evaporated into the environment.

Besides dependence of the specific air flow rate, the drying rate of paddy was strongly affected by the inlet air temperature as shown in Figure 4. Higher temperatures resulted directly in faster reductions of moisture content because of greater differences between drying air and paddy surface temperature, thereby providing higher paddy temperatures, which remarkably improved the diffusion rate of moisture inside the paddy.

3. Paddy quality

3.1 Head rice yield

Figure 5 shows the relationships between the percentage of relative head rice yield and the final moisture content of paddy (M_f) at a inlet temperature of 150°C, a hold up of 30 kg and initial moisture contents (M_i) of 31.1, 37.8 and 45.6% d.b. It appears that the percentage of relative head rice

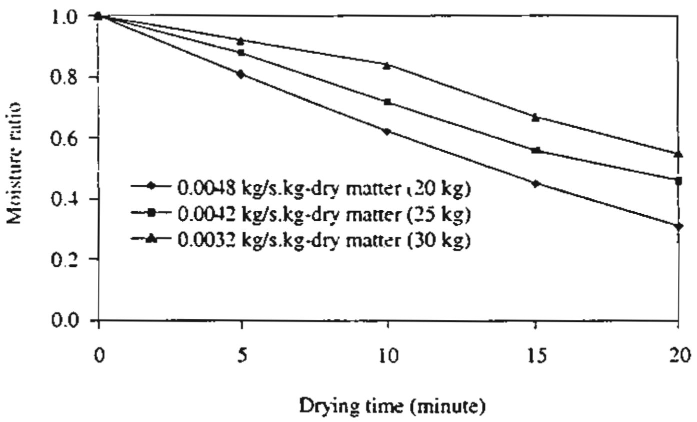

Figure 3 Evolution of moisture content of paddy at different specific air flow rates. (M_i = 45.6% d.b., T_i = 150°C)

yield for various final moisture levels relative to reference sample is higher for the initial moisture contents of 37.8% and 45.6% d.b, with showing the values higher than 100% whereas the relative head yield reduces continuously with decreased final moisture content for the case of initial moisture content of 31.1% d.b.. Such higher percentages of head rice yield can be explained by the gelatinisation effect (Taweerattanapanish *et al.*, 1999) which molecules of starch granules are vibrated and the chemical bonds are deformed, resulting in the water molecules transported to them and then formed the hydrogen bonding. Eventually, when both moisture and temperature levels are appropriated, the gelatinisation can be occurred. For temperatures of 130 and 140°C and initial moisture contents of 37.8 and 45.6% d.b., the results were given a similar trend to Figure 5, showing the increase of relative head rice yield.

In Figure 6, however, the percentage of relative head rice yield for initial moisture content 31.1% d.b. reduced progressively with decrease of final moisture content. In addition, in this case, the inlet air temperatures seriously affected relative head rice yield; significantly lower relative head rice yield obtained by using higher drying temperatures under the same final moisture level. This seems to have different behaviour from Figure 5 in

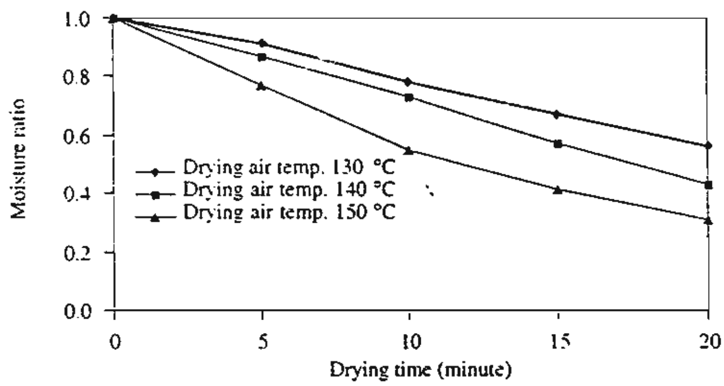

Figure 4 Evolution of moisture content of paddy at different drying air temperatures at the dryer inlet. (M_i = 31.1% d.b., hold-up = 20 kg)

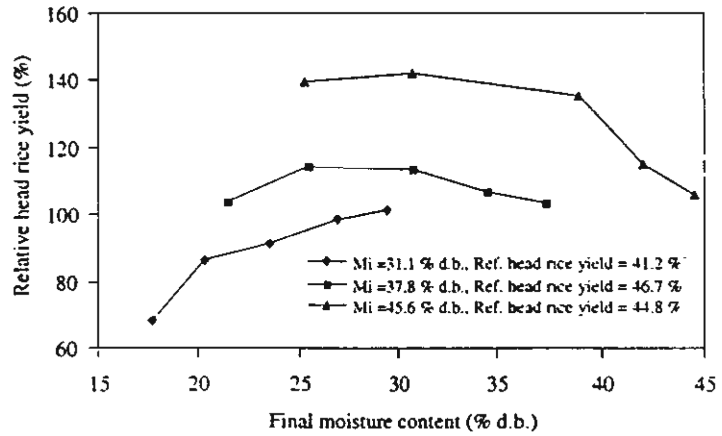

Figure 5 Relative head rice yield at different initial moisture contents. (M_i). (T_i = 150°C, hold-up = 30 kg)

particular at moisture content higher than 37.8% d.b. exhibiting the remarkable increase of head rice yield during the reduction of moisture content. The resulting reduction of head rice yield for paddy possessing lower moisture contents is due to large gradient of moisture inside the grain kernel leading to the formation of stress crack.

Comparing to the results of paddy dried by the fluidised bed technique (Taweerattanapanish *et al.*, 1999), the qualities of dried paddy from such both approaches were nearly the same. A superior percentage of head rice yield can be obtained if the moisture content of paddy is not too low. Besides the head rice yield, the rice whiteness was also an important issue, which was used for concerning the paddy quality, and discussed in the following section.

3.2 Rice whiteness

Figure 7 shows the relationship of the relative rice whiteness with the final moisture content

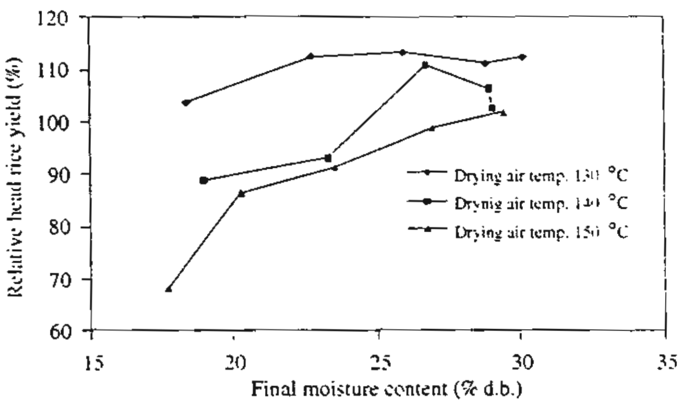

Figure 6 Relative head rice yield at different drying air temperatures at the dryer inlet. (M_i = 31.1% d.b., hold-up = 30 kg)

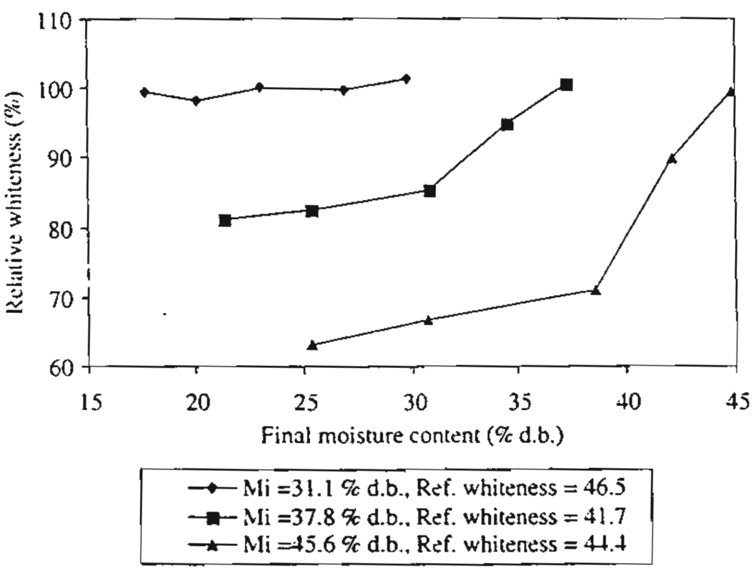

Figure 7 Relative whiteness at different initial moisture contents (M_i). (T_i = 150°C, hold-up = 30 kg)

(M_f). At initial moisture contents of (M_i) 31.1 - 45.6% d.b., a hold-up (H) of 30 kg and an inlet air temperature (T_i) of 150°C, the results were indicated that the relative rice whiteness continuously decreased during period of reducing moisture content. The relative rice whiteness curve of initial moisture content of 45.6% d.b. shows a steep drop in the values of colour from 100% at start to 62% at moisture content of 25% d.b. whereas the rice whiteness values for initial moisture content of 31.1% d.b. insignificantly alter over the various values of final moisture content. The reason for this cause is that the drying time for removing the moisture to various levels is different for each of initial moisture content; the case of moisture content of 45.6% d.b. is spent the longest one. The drying time relating closely to the final moisture content is therefore a prominent contribution to colour change of paddy.

The influence of drying air temperature on rice whiteness is shown in Figure 8. It was clearly evident that at the same final moisture content, the use of higher drying temperature provided lower values of the relative rice whiteness, in spite of shorter drying time. In addition, in all cases, the colour rapidly decreased at initial period of drying and then slowly declined at the remain of drying period. For the other hold ups, the trends of relative rice whiteness is similar to Figure 8, showing the decrease of their values with final moisture contents. The colour change of paddy from white to pale yellow during heating process can be explained by the non-enzymatic browning reaction (Tanthapanichkule, 1990).

From the quantitative consideration of the paddy qualities in terms of the whiteness and the head rice yield, the acceptable drying condition, which favours the high drying capability and the acceptable qualities, should be the inlet air temperature not higher than 150°C and the subsequent moisture content after drying should not be lower than 21% d.b.

4. Energy consumption

Figure 9 shows the influence of inlet air temperature on the specific primary energy consumption for the heater and the electrical fan (multiply the experimentally measured energy consumption by a factor 2.6). The energy consumption for the heater varied linearly with inlet air temperature whilst the consumed energy for the fan was independent to temperature. With changing the specific air flow rates (by increasing the air flow rate) as shown in Figure 10, the specific primary energy consumption was also altered in a way that the energy consumption at lower air flow rates was rela-

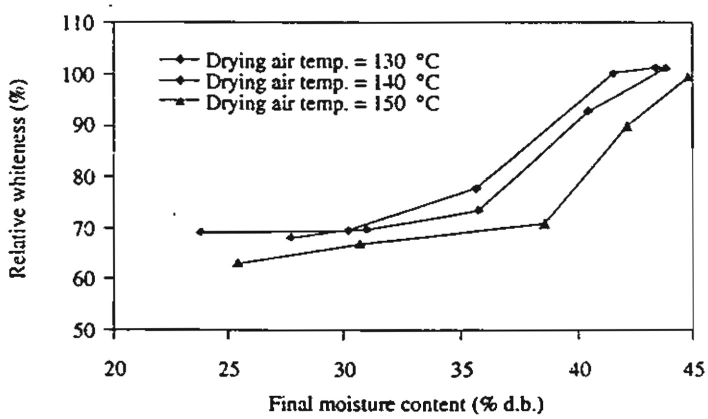

Figure 8 Relative whiteness at different drying air temperatures at the dryer inlet. (M_i = 45.6% d.b., hold-up = 30 kg)

tively lower than that at higher air flow rates.

5. Drying kinetic model

Refer to Figure 3 showing that the moisture content of paddy decreased linearly with drying time, the following linear form of drying equation was therefore proposed to predict the moisture reduction in term of moisture ratio (MR):

$$MR = a+bt \quad (3)$$

Where a and b = drying constant values
t = drying time, minute

$$MR = \frac{Mt - Meq}{Mi - Meq} \quad (4)$$

M_t = moisture content of paddy at time t, dry basis fraction

M_{eq} = equilibrium moisture content of paddy, dry basis fraction

M_i = initial moisture content of paddy, dry basis fraction

The multiple regression approach was used for correlating statistically the drying constants with drying conditions such as the inlet air temperature

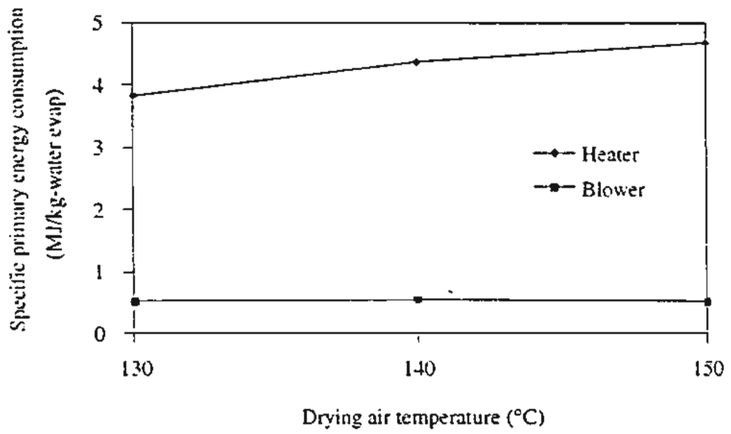

Figure 9 Relationship between specific primary energy consumption and drying air temperature at the dryer inlet. (hold-up = 25 kg, M_i =45.6% d.b. and M_f =21% d.b.)

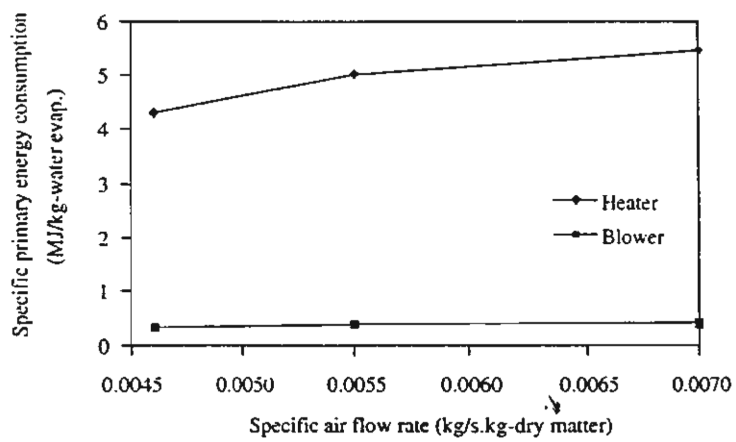

Figure 10 Relationship between specific primary energy consumption and specific air flow rates. (hold-up = 25 kg, M_i = 45.6% d.b., M_f = 21% d.b.)

(T_i), °C and hold-up(H), kg. The following appropriately selected forms of drying constant equations as follows:

$$a = 1.51167-0.01833H-0.003961T_i+0.000143H \cdot T_i \quad (5)$$

$$b = 0.077656-0.002367H-0.000889T_i-0.000034H \cdot T_i \quad (6)$$

The value of average squared predicting error (ASPE) between the results from experiment and calculation was 0.00129. Note that this equation did not intrinsically mean that the moisture transfer inside paddy falled into the range of constant drying rate period, but in fact, it was in the falling rate period. The comparisons between the predicted values and all experiment conditions are exhibited in Figure 11.

CONCLUSION

The experimental study of paddy drying with two-dimensional spouted bed technique with draft plates can be concluded as follows:

1. The minimum spouting velocity at dryer inlet area 4×15 cm^2, width of spout 8 cm, entrance height 10 cm and bed hold-up 20-30 kg was in range of 15.4-16.4 m/s. The maximum pressure drop at start of spouting state was in range of 2000-3600 Pa and spouting drop was in range of 1400-2300 Pa.

2. Drying air temperature and specific air flow rate significantly affected paddy drying rates, *i.e.* as either the specific air flow rate or inlet air temperature increased, drying rate increased. The empirical form of first polynomial equation was described adequately the moisture transfer inside the paddy kernel.

3. Percentage of head rice yield increased when paddy had initial moisture contents of 37.8 and 45.6% d.b. and was dried at temperature higher than 130°C. In contrast, for lower moisture content of 37.8% d.b., the relative head rice yield was decreased although the inlet temperature increased. Rice whiteness decreased when initial moisture content increased, while drying air temperature slightly affected to rice whiteness.

4. Specific energy consumption for heater moderately proportionally increases with increase of both temperature and specific air flow rate whereas for fan, it was independent to them.

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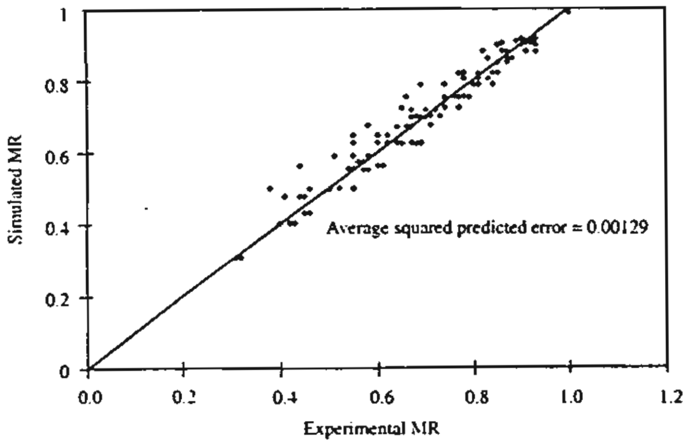

Figure 11 Comparison between simulated and experimental moisture ratios (MR) of paddy.

stitute for kindly assisting in rice quality testing.

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Study of Parameters Affecting Drying Kinetics and Quality of Corns

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ABSTRACT

The objectives of this research are to investigate factors affecting on drying rate of high moisture corn at high temperature with fluidisation technique and to develop a mathematical model for predicting drying rate. There were three following steps of drying process: 1) rapid drying using fluidised bed dryer at inlet drying air temperature of 130-170°C, 2) corn tempered for period of 40-180 minutes under the same temperature as drying from the step 1 and 3) drying with ambient air. Drying kinetic shows the inlet air temperature and the specific airflow rate significantly affecting the drying rate. Amongst three semi-empirical drying equations (Wang and Singh, Page and Lewis), Page's equation provides the best prediction.

This study also aims to study the quality of corn dried in each step. Corn qualities in terms of *aflatoxin* content, percentages of breakage and stress crack, and colour change have been considered. Experimental results show that *aflatoxin* content in dried corn does not change. Breakage and cracking depend strongly on final moisture content and are relatively dependent to temperature. Tempering provides the improvement of colour while inlet air temperature has no effect.

Key words: drying kinetics, grain, quality

INTRODUCTION

One of the most important agricultural products in Thailand is corn. The need of corn in the feed mill and the other food industries tend to be increased considerably. Corn can be produced in two seasons. The first one is grown in the period from April-May to July-August-September, which falls in the rainy season. The second crop is started from July-August-September to October-November-December and harvested at the end of the rainy season. Since a very large amount of corn produces in the first crop, a serious problem of poor corn quality has been faced if corn could not be immediately dried. This is by virtue of the fact that fresh corn is usually harvested at moisture content more than 23% wet basis. The micro-organism already infecting the corn can grow up easily under conditions of such moisture levels coupled with a suitable water activity especially higher than 0.85 (Wongurai *et al.*, 1992). Most species found in corn are likely to *A.flavus* and *A.parasiticus*. Both moulds can yield the poison substances known as *aflatoxin B-1* within 2-8 days (Laecy *et al.*, 1986) if the environmental conditions are suitable. This substance causes seriously the cancer at different organs of human. Drying can contribute to corn quality since moisture content is the most significant

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factor affecting changes in quality of corn. Numerous approaches can be applied for reducing moisture content. Each method has the advantage and disadvantage. The use of ambient air is the simplest one. When corn with moisture content higher than 23% wet basis was dried by blowing the ambient air through the bulk of corn. It showed that after its moisture content reduced to the desired value of 14 % wet basis, the level of *aflatoxin B-1* significantly increased to 250 ppb while the amount of *aflatoxin B-1* at the beginning was nil (Prachayawarakorn *et al.*, 1995). This technique seems to spend so long drying time that some amounts of corn were infected and hence the *aflatoxin* could be occurred. The artificial drying method would therefore be an appropriate choice because of rapid removal of moisture contents in the process.

There are many types of artificial dryer being used in grain industries, for example LSU dryer (LSU = Louisiana State University), cross-flow dryer, spouted bed dryer and fluidised bed dryer. The latter one is of the main interest in this work. By fluidised technique, grains are transformed into a like fluid after thoroughly mixed with a sufficiently high air velocity. Under the fluidised state, the drags force on the grain particles balance the gravitational force pulling on them. Therefore, the grains remain in a semi-suspended condition. This inherent phenomenon provides the main advantages over the other types of dryer. The intensively mixed solids throughout the bed provide almost uniform temperature and moisture content. High heat and mass transfer rates are possible because of very good contact between air and solid. Thus, at high moisture level, a large proportion of water concentrated near the surface of solid particles can be removed quickly whilst the small one existing deeply inside the kernel still remains and is extremely very difficult to vaporise it although the capable of drying air allows to be powerful. There are some workers studying the corn drying using the fluidised bed technique (*e.g.* Soponronnarit *et al.*, 1997a). They investigated the factors affecting the drying rate and the quality. They reported that moisture movement inside the kernel was controlled by diffusion and constant drying rate period was absent. The inlet air temperature is strongly influence to moisture reduction whilst the air velocity and the bed depth become relatively significant factor. In addition, when the drying was proceeded successively, the physical change was virtually found. The amount of corn tracing the stress crack and the breakage significantly increased following with the increased temperature and the reduced moisture content whilst it did not change with air humidity (Soponronnarit *et al.*, 1997b). So far, the colour was relatively changed of which the value of "a" representing red increased with the increase of temperature and of drying time whilst the value of "b" representing yellow decreased.

Such changes lead to a serious problem in that the micro-organism, then inducing the occurrence of toxin substances, can easily attack the broken or cracked corn. In addition to easy infection, such physical damage is also an important measure of quality in processing operations such as cereal and snack food measuring. This cause took us to explore the way of improving the dried corn quality. One of the common approaches that can be improved its quality is a tempering process. This process allows the reduced moisture gradient inside the grain and eventually the moisture concentration at local positions inside the corn kernel becomes relatively identical. Foster (1973) showed that tempering process could reduce the degree of stress cracking during artificial drying of corn. For the paddy drying, Steffe and Singh (1980) also concluded that the additional tempering stage in the drying process was able to sustain head rice yield as compared the conventional one where the paddy was dried in a single pass. Despite its importance to grain quality, the research works have been less interest to provide an important information of tempering time. This fact may be useful not only for grain quality improvement but also for energy consumption.

The objectives of this work are to explore the effect of tempering period on the corn quality in terms of colour, stress crack and breakagibility and the operating parameters such as temperature, bed depth and airflow rate affecting the removal of moisture content of corn. Its moisture content was eventually reduced to 14% wet basis in order to inhibit the growths of *A.flavus* and *A.parasiticus*.

MATERIALS AND METHODS

Corn was dried by a batch fluidised bed dryer mainly composed of a cylindrical shaped stainless chamber with a 20 cm diameter and a 140 cm height, as shown in Figure 1. In order to save economically energy consumption, some proportions of the exhausted air are recycled and then mixed with the fresh air. The mixed air after reheated with 4 element heaters, each of elements having 3 kW power (total 12 kW), is flowed through

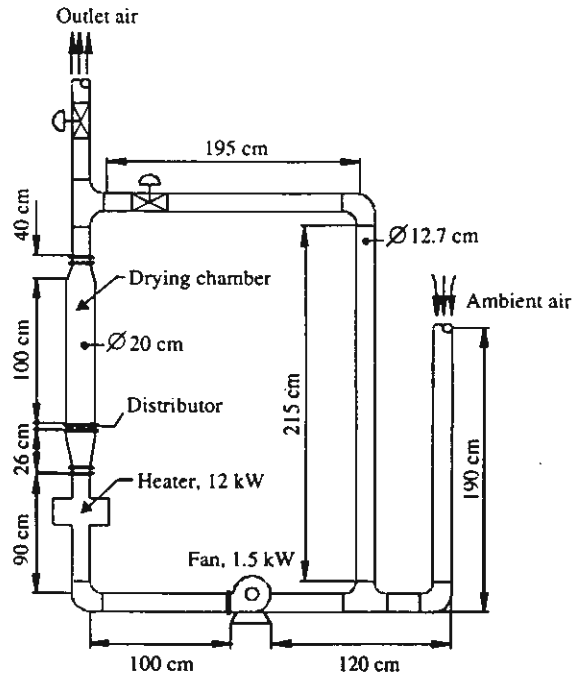

Figure 1 Schematic of experimental fluidized bed corn dryer.

the dryer again. A PID controller with an accuracy of ± 1°C was used to control the inlet temperature. In the fluidised bed system, it requires a high air flow rate and a high-pressure drop, so that a backward-curved blade centrifugal fan driven by a motor power of 1.5 kW was selected. In order to obtain a desired inlet air velocity and maintain performance of the system, a mechanical variable speed unit was chosen to control the revolution of fan.

Drying kinetics

Freshly harvested corn, type Suwan 1, was rewetted to obtain desired moisture content of 43% dry basis. The rewetted corn was then kept in a temperature-controlled room at 5-10°C for 5 or 7 days in order to get the uniform moisture content inside the grain kernel. The following rewetted corn was dried to moisture content of 23% wet basis. The experiments were carried out at the following conditions: inlet temperatures of 130, 150 and 170°C and bed depths of 4, 6 and 8 cm. The air velocity was kept at a constant value of 3 m/s throughout these experiments. This value is approximately 1.6 times higher than the minimum fluidisation velocity for corn of which the value was approximately 1.8 m/s (Soponronnarit *et al.*, 1997a). Such a value beyond the minimum velocity was certainly sure that every moist corn could rigorously mix with the drying air. The relatively similar moisture content throughout the bed is a consequent result. If the air velocity is set too high, then the corn is increasingly agitated due to the formation of large bubble size, detrimental effect on the interchange of heat and mass transfers between gas and solid phases. The samples drawn from the dryer in every minute were then kept in a hot air oven at a constant temperature of 103°C for 72 hours to determine the moisture content

Thin layer drying equations

Development of mathematical models to describe the drying of porous solids is of important topic in literature. Models are needed to enable process design and to minimise energy consumption and total costs subject to quality constraints. In the fluidisation technique, the sufficiently high air velocity provides the body of corns behaving like a liquid, so that at this stage the grains feel "weightless" and move randomly and severely within the bed. Every kernel is therefore suspended completely in the air. Such phenomenon results in the insignificant change of the air properties along the bed depth and the grain temperature increased rapidly and then approached to the inlet air temperature for a short period of time. So far, the moisture content at surface is reduced speedily and consequently equilibrated with the existing air. Under this condition, the theoretical diffusion model can explain the moisture transfer inside single kernel. Unfortunately, the theoretical model predicts inaccurately since the grain often has an irregular shape and the mechanism of moisture movement inside the grain has been being questioned. In practice, the empirical thin layer drying equation has therefore been applied. Three following forms of thin layer drying equation were proposed in this work. First, the Lewis' equation (1921) is given by

$$MR = \exp(-bt) \quad (1)$$

where b = drying constant depending on the operating parameter

t = drying time, min

$$MR = \text{moisture ratio} = \frac{M(t) - M_{eq}}{M_{in} - M_{eq}}$$

$M(t)$ = moisture content at time t

M_{in} = initial moisture content

M_{eq} = equilibrium moisture content

The equation (1), known as Newton's law of cooling, is assumed the negligible moisture gradient inside the grain kernel, indicating that the resistance of diffusion is insignificant. Wang and Singh (1978) was then simply modified equation (1) by adding one more drying constant. Wang and Singh's equation can then expressed as

$$MR = a \cdot \exp(-bt) \quad (2)$$

where a is drying constant similar to the constant b in equation (1). Finally, the purely empirical equation is demonstrated. Page's equation (1952) also expresses moisture ratio as a form of exponential function of drying as shown in equation (3),

$$MR = \exp(-bt^a) \quad (3)$$

Equation (3) is often described favourably the experimental data (Soponronnarit and Prachayawarakorn, 1994).

Drying constants determined from all these equations were analysed using the non-linear regression approach in the commercial package SPSS (Statistical Package for the Social Science). The equation to describe them is not based on the theoretical formulation. Simple or complex one may be chosen arbitrarily by fitting it with parameters influencing to drying rate such as specific airflow rate and temperature. Details will be discussed in the following section. However, the appropriate expressions proposed for *a* and *b* are given by

$$a = A_1 + A_2T + A_3S_P + A_4T.S_P + A_5\ln(S_P) \quad (4)$$

$$b = B_1 + B_2T + B_3S_P + B_4T.S_P + B_5\ln(S_P) \quad (5)$$

where A_1-A_5 and B_1-B_5 = constant

T = inlet air temperature

S_p = specific air flow rate

Quality test

The successful or failure in drying process can be justified from the grain quality obtained. The criterion for considering the grain quality in each species is very different. However, for corn, one of the most important qualities that market is often used is the amount of *aflatoxin* B-1 in corn, besides breakage, stress crack and colour. Four quality aspects for examples *aflatoxin*, breakage and stress crack were therefore subject to consider in this work. The amount of *aflatoxin* was detected by using HPLC with the corn sample of 50 g. In each condition, three samples were tested. One-way analysis of variance (ANOVA) was performed to examine whether the amount of *aflatoxin* before and after drying in each stage is changed or not by using 95% confident level.

For the stress crack and the breakage, the visual inspection under light was employed with 200 g of corn sample. Each kernel was classified into three classes: broken, cracked (multiple and single) and undamaged. The percentage for each class was normalised by dividing the weight of corn kernel in each category by the total weight. Multiple cracking was often found in this work. A colour meter, Juki JP 7100p, determines grain surface colour. The values of a, b and L in Hunter system corresponding to red, yellow and lightness, respectively were read. The corn samples after final drying stage were checked carefully the above mentioned qualities.

In testing quality, after the corn was dried to 23% dry basis, it was then tempered in an airtight container for periods of 40, 120 and 180 minutes respectively under the same inlet air temperature. Finally, the corn was dried again using ambient air until the moisture content reached 16% dry basis. To obtain the accurate results, the experiment in each condition was three replicates.

RESULTS AND DISCUSSION

Effects of parameter on drying rate

The inlet air temperatures used in this experiment as shown in Figure 2 are very high compared to other techniques that are normally operated at temperatures between 50°C and 70°C for drying grains. This may have crossed the minds of many scientists and innovators, but Soponronnarit and Prachayawarakorn (1994) showed that it was possible to dry grain at high temperature range without significant loss of grain quality if the drying process was controlled effectively. Figure 2 represents the influence of inlet air temperatures on the reduction of moisture ratio at 6 cm bed depth and 3 m/s air velocity indicating that faster moisture removal relates closely to higher inlet temperatures. This effect is increasingly important during the final period of drying at which the moisture content

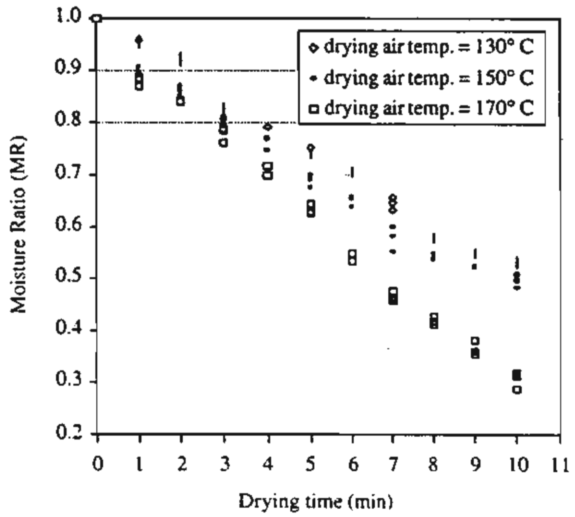

Figure 2 Effect of drying air temperature on moisture ratio (initial moisture content 43% d.b., drying air velocity 3 m/s and bed height 6 cm).

is rather low; more release of moisture content requires higher temperature difference between the solid and drying medium. As can be seen in Figure 2, the degree of moisture content at different temperatures starts remarkably different after 6 minutes whilst at the early period, the temperature is less important effect.

The drying rate is also relatively affected by the specific airflow rate, defined as the ratio of mass of drying air to dry mass of corn loaded into the chamber. As shown in Figure 3, moisture extraction relatively increases with the increase of specific airflow rate under the identical operating condition. In the configuration investigated, the quantity of corn in each case was different whilst the airflow rate was kept a constant value and the change in the amount of corn did not effect behaviour of fluidised corn. When corn was subjected to the drying air, some proportions of energy were transferred to the grains, resulting in some evaporation. By such a situation, the surrounding conditions inside the chamber were therefore changed with changing the amount of corn; the quantity of water vapour around the corn kernel directly related to the capacity of

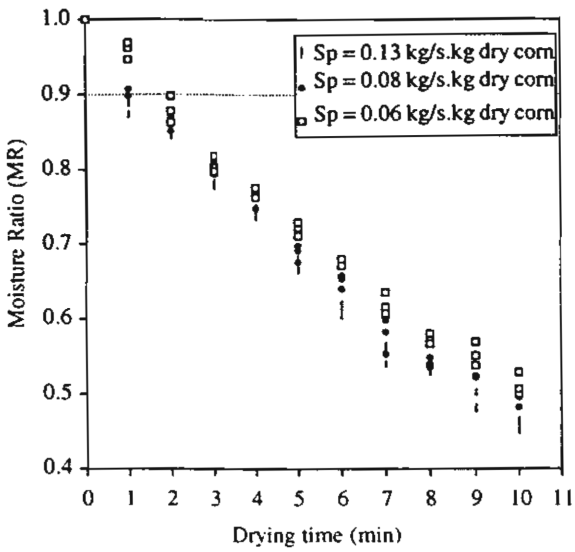

Figure 3 Effect of specific air flow rate (Sp) on moisture ratio (initial moisture content 43% d.b., drying air velocity 3 m/s and drying air temperature 150°C).

corn in the dryer. Hence, this effect results in drying rate.

Comparison of thin layer equations

Three thin layer-drying equations were used to validate the experimental data. The fitted data were obtained from the single pass of corn drying, starting from 43% dry basis until to 16% dry basis. All these equations can predict the moisture content insignificantly different at the beginning period of drying particularly higher moisture range of 23% dry basis as represented in Figure 4 whereas their predictions have a small difference near the end of drying period at which the moisture content is relatively low. Only Page's equation is found to yield the best fit to the experimental data. This may be because when the moisture content start reducing from such a high level to lower level, the large moisture gradient exists inside the corn, so that the equation (1) and (2) predict inaccurately.

Drying constants in those equations fitted statistically with the above-mentioned factors are thus given by the following equations:

Lewis's equation

$$b = 737 + 0.0006000T - 0.8420S_p + 0.003700T.S_p + 0.06590\ln(S_p) \quad (R^2 = 0.9778) \quad (6)$$

Wang and Singh's equation

$$a = 0.3019 - 0.0002000T + 2.001S_p + 0.002000T.S_p - 0.2112\ln(S_p)$$

$$b = 0.09332 - 0.0005000T - 0.60888S_p + 0.003900T.S_p + 0.04171\ln(S_p) \quad (R^2 = 0.9782) \quad (7)$$

Page's equation

$$a = -3.089 - 0.001000T + 2.703S_p + 0.1474T.S_p - 1.586\ln(S_p)$$

$$b = 0.6017 + 0.002100T - 0.07010S_p - 0.01790T.S_p + 0.2510\ln(S_p) \quad (R^2 = 0.9832) \quad (8)$$

Based on the R^2 values, Page's equation is the most suitable equation that can describe the corn dying in the fluidised bed dryer. For the other conditions, the results also show similar trend to Figure 4.

Corn quality

In testing the corn quality, the experiments were performed at the conditions of 43% dry basis initial moisture content, 3.0 m/s air velocity, 8 cm bed depth and 170-180°C inlet air temperatures.

Aflatoxin

In testing the change of *aflatoxin* quantity by heat treatment, the corn samples were dried to 23 and 16% dry basis under the previously mentioned temperature range. One way-ANOVA shows that although the inlet temperature is increased, the *aflatoxin* is insignificantly changed in amount after completed the process of drying.

In fact, the *aflatoxin* could be removed by heat treatment (temperature of 250°C), at which it is the melting point (Feull, 1966). In contrast, Cucullu *et al.* (1966) reported that even though the

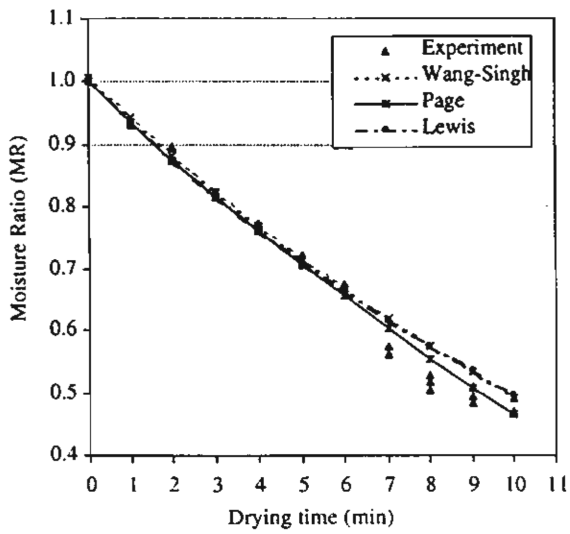

Figure 4 Comparison between thin layer drying equations and experimental results (initial moisture content 43% d.b., drying air velocity in drying chamber 3 m/s, bed height 4 cm and inlet air temperature 130°C).

temperature is not high enough to melt the *aflatoxin*, the quantity of the *aflatoxin* substance in peanut could possibly be reduced by roasting at a temperature of 150°C for 90 minutes. From that point of view, we tried exploring the heat treatment approach using the fluidised bed technique. But, corn can be not contacted with high drying air temperature for a long drying period due to the serious physical damage, as we will discuss in the following section. Thus, the corn was initially dried at temperature of 160°C and then followed with tempering for periods of 120 and 180 minutes under the corresponding temperature. The results still show the same trend as the previous ones, indicating invariable amount of *aflatoxin*. This is likely to treat the *aflatoxin* by such an approach ineffectively.

Breakageability and stress crack

Figure 5 shows the relationship between breakageability or stress crack and inlet temperatures under various final moisture levels. Major contribution of drying induced the stresses is the non-uniform moisture content. The stresses are tensional force near the boundary of dried material, so that they give the rise to the crack of dried body (Musielak, 2000). Refer to Figure 4, at the early stage of corn drying during which moisture content is higher than 19% wet basis, the moisture gradient inside the corn kernel expected to be very small, as indicated by Lewis's equation, so that such a small difference can not encourage the stresses. As a result of this, the percentage of stress crack is almost constant in spite of temperature increased as shown in Figure 5. In addition, the percentage of breakageability is not changed. When the corn was dried further and then approached to 14% wet basis, the percentage of stress crack increases to approximate 11.5% with respect to the previous one with showing value of 9.5% (see the cross symbol). The increase of stress cracking also contributes importantly to the breakagibility. The percentage of breakagibility in this case increases more than twice as compared to the one that corn dried to 19% wet basis. When using drying air at

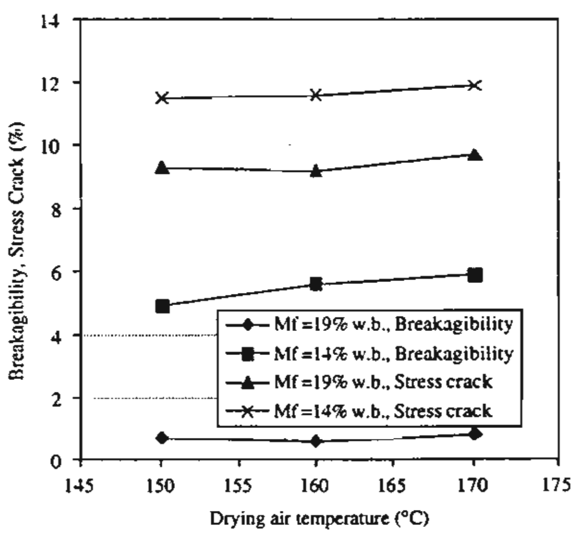

Figure 5 Influence of drying air temperature on the stress crack and breakage at difference final moisture contents, Mf (initial moisture content 30% w.b.).

170°C, the broken corn has a shape similar to the popcorn. From this figure, the temperatures seem to insignificant effect on the stress crack and the breakagibility for all cases whereas the moisture content plays an important role. Similarly, Peplinski *et al.* (1994) reported that the total number of kernel stress cracks did not change significantly over a wide range of drying temperatures.

However, the tempering period was then included between the drying stage by starting tempering since the corn was reduced to 23% dry basis. After that, it was dried to 14% wet basis with the ambient air. The corn quality is now improved. As shown in Figure 6, the number of cracked corn is relatively reduced following the increase of tempering time. By contrast, the percentage of breakagibility insignificantly changes despite the tempering time is increased with showing the value of approximate 5.5%. This value is almost exactly the same amount as the previous case that corn was dried to 14% wet basis shown in Figure 5. The explanation of this cause has not been cleared yet and it is subjected to more work being investigated.

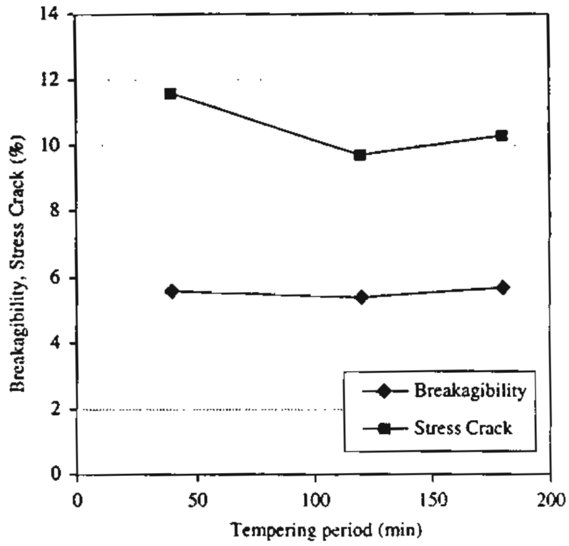

Figure 6 Effect of tempering periods on the breakage and stress crack (initial moisture content 30% w.b. and inlet air temperature 160°C).

Colour

Following previous work by Soponronnarit *et al.* (1997b) showed that a and b values changed with drying times and temperatures. In their work, the corn was dried continuously until its moisture content reached 16% dry basis. In order to improve the colours, the concept similar to the above-mentioned case was used, that is, the additional tempering period between drying stage. Figure 7 shows the evolution of a, b and L values with tempering periods at 160°C. The a values linearly increase with tempering time whilst b and L values monotonically decrease. At the tempering time more than 120 minutes, the tempered corn becomes much more intense colour than the normal level, related to the resulting change of a, b and L values. This result is similar to the work reported by Chotijukdikul (1997). On the contrary, the colour is acceptable at tempering period of 40 minutes. It was visually observed that the colours were insignificantly changed after the corn was tempered for period of 40 minutes in spite of the fact that before tempering, the corn dried at higher

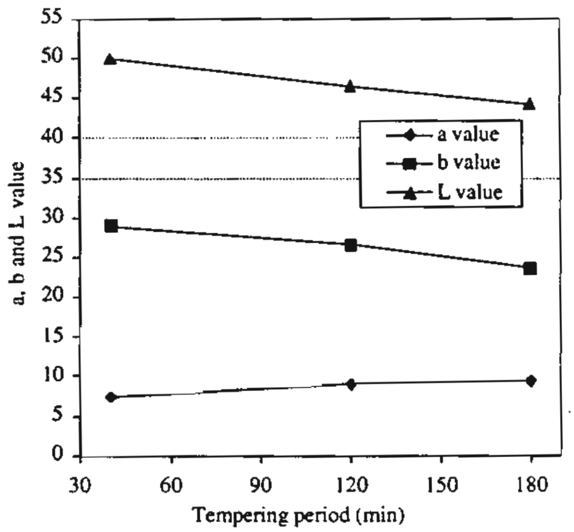

Figure 7 Effect of tempering periods on the value of a, b and L (initial moisture content 30% w.b. and inlet air temperature 160°C).

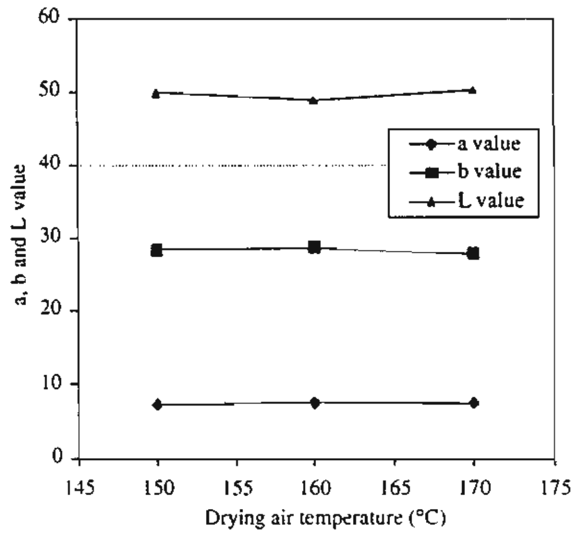

Figure 8 Effect of drying air temperature on the value of a, b and L (initial moisture content 30% w.b., final moisture content 19% w.b. and tempering period 40 minutes).

temperatures, resulting in lower moisture contents, had more intense colour. This can be seen in Figure 8 showing the values for a, b and L are all insignificant deviations with temperatures for the tempering period of 40 minutes. The explanation of such a cause may be because when the dried corn was subjected to temper in the airtight container only for a short period, some evaporation can occur, resulting in grain temperature reduced, and at the same time, the change of the colours cannot be transformed completely. The colours can, therefore, be recovered again. However, if it was corrected for a longer time, then the grain temperature increased and approached to a fixed temperature for tempering. Hence, the grain colours became poorer.

CONCLUSIONS

The results of this study can be concluded as the followings:

1) Specific airflow rate and inlet drying air temperature are important factors influencing drying rate of corn in fluidised bed dryer.

2) Amongst three popular thin layer equations, Page's equation is the most suitable equation predicting in agreement with the experiments.

3) The fluidised bed drying technique can inhibit the increase of *aflatoxin* level. With this technique, the *aflatoxin* is not enabled to destroy by heat treatment although the temperature range used is very high.

4) Final moisture content of corn is a main effect on breakagibility and stress crack whilst inlet air temperature is a less significant factor. Over range of high temperature, the corn should not be dried to 14% wet basis in a single pass. Tempering is recommended for corn drying.

5) Tempering period in drying process play a key role in improving the corn colours in terms of a, b and L values.

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Effect of Temperature on Soybean Quality Using Spouted Bed Technique

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ABSTRACT

The effect of temperature on moisture reduction rate and soybean qualities using a two-dimensional spouted bed dryer has been studied. Air velocity was varied in a range of 15.86-20.50 m/s, with a fixed hold-up of 25 kgs. The soybeans with initial moisture levels varying between 28 and 32% dry basis were dried to 12-17% dry basis using inlet air temperatures of 120-150°C. The experimental results indicate that higher temperatures provide faster moisture reduction rate.

The qualities of soybean have also been considered in terms of stress cracking, breakage, urease activity and protein solubility in 0.2% KOH. It is shown that the percentages of cracking and breakage depend on temperature, final moisture content and degree of collision of kernel with deflector. The percentages of stress crack and breakage lie in the range of 50-60% and of 3-24%, respectively. The urease activity and protein solubility are accepted with slightly changing in the protein quality.

Key words: grain; pH change; protein solubility

INTRODUCTION

Soybean (*Glycine max* (L.) Merrill) is classified as an oilseed legume which contains both of heat-labile anti-nutritional factors, i.e. trypsin inhibitor, hemagglutinin, and heat-stable anti-nutritional factor, i.e. saponin. These factors directly affect the growth of various species of animals (Liener, 1988). The trypsin inhibitor (TI) is the one to be of practical interest in considering the quality of soybean because it increases the secretory activity of pancreas, causing the pancreatic hypertrophy and the growth depression. When soybean is treated with sufficiently high heat processing, the trypsin inhibitor and the other anti-nutritional factors are inactive, but their nutritional components are improved (White *et al.*, 1967; Faber and Zimmerman, 1973; Qin *et al.*, 1996).

White *et al.* (1967) reported growth response of chick fed. In the work, soybean used as a protein supplement was treated by different methods such as autoclaving, extrusion and infrared roasting. It indicated that gain weight and feed to gain ratio depended on the methods of treatment. The extruded soybean gave higher gain weight and feed to gain ratio than the roasted and autoclaved soybeans. Faber and Zimmerman (1973) studied the growth response of baby pigs, which was similar to the report of White *et al.* (1967).

In addition to the above-mentioned heat treatment processes, fluidization technique has recently been applied for eliminating the trypsin

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