รายงานวิจัยฉบับสมบูรณ์

โครงการ: การอบแห้งเมล็ดพืชโดยเทคนิคสเปาเต็ดเบดที่สามารถควบคุมอัตราการไหลของอากาศในดาวน์คัมเมอร์ได้

โดย ดร.ฐานิตย์ เมธิยานนท์ และคณะ

มิถุนายน 2547

สัญญาเลขที่ TRG4580085

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คณะผู้วิจัย		สังกัด
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สนับสนุนโดยสำนักงานกองทุนสนับสนุนการวิจัย

กิตติกรรมประกาศ

ขอขอบคุณสำนักงานกองทุนสนับสนุนการวิจัยที่ให้การนับสนุนทุนวิจัยและคุณวิบูลย์ เทเพนทร์ สถาบันวิจัยเกษตรวิศวกรรม กลุ่มงานวิจัยวิศวกรรมหลังการเก็บเกี่ยว ที่ให้ความอนุเคราะห์ในการใช้เครื่องมือวิเคราะห์คุณภาพข้าวเปลือก

บทคัดย่อ

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1. **รหัสโครงการ :** TRG4580085
2. **ชื่อโครงการ :** การอบแห้งเมล็ดพืชโดยเทคนิคสเปาเต็ดเบดที่สามารถควบคุมอัตราการไหลของอากาศในดาวน์คัมเมอร์ได้
3. **ชื่อนักวิจัย :**

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6. **เนื้อหางานวิจัย :**

6.1. วัตถุประสงค์

6.1.1. ออกแบบและสร้างเครื่องอบแห้งสเปาเต็ดเบดสำหรับห้องปฏิบัติการโดยสามารถควบคุมอัตราการไหลที่เข้าสู่ดาวน์คัมเมอร์ได้

6.1.2. ศึกษาผลกระทบของอัตราการไหลของอากาศในบริเวณดาวน์คัมเมอร์ต่ออัตราการอบแห้ง และคุณภาพข้าวเปลือกหลังการอบแห้ง

6.1.3. หายุทธวิธีที่เหมาะสมในการอบแห้งข้าวเปลือกโดยเทคนิคสเปาเต็ดเบด

6.1.4. เปรียบเทียบสมรรถนะระหว่างเครื่องอบแห้งสเปาเต็ดเบดกับเครื่องอบแห้ง ฟลูอิไดซ์เบด

6.2. ระเบียบวิธีวิจัย

ในการทดลองใช้ข้าวเปลือกเป็นวัสดุอบแห้ง เครื่องอบแห้งแบบสเปาเต็ดเบดแบบสองมิติซึ่งใช้การอบแห้งแบบงวดพร้อมอุปกรณ์อื่นๆ แสดงในรูปที่ 1 ส่วนบนของเครื่องอบแห้งประกอบด้วยผนังในแนวดิ่งและส่วนล่างจะประกอบด้วยผนังในแนวลาดเอียง โดยด้านหน้าของห้องอบจะเป็นกระจกใสทนความร้อนเพื่อให้มองเห็นลักษณะการเคลื่อนตัวของเมล็ดพืชได้ ผนังเอียงทำมุม 60° กับแนวราบ ช่องอากาศเข้าด้านล่างของเครื่องอบมีขนาดกว้าง x ยาว เท่ากับ 30 mm x 84 mm ทางด้านล่างของเครื่องอบแห้งจะมีทางเข้าของอากาศอยู่สามช่องคือ 1) ช่องเข้าอากาศตรงกลางสำหรับจ่ายอากาศเข้าสเปาต์ 2) และ 3) เป็นท่อขนาดเส้นผ่านศูนย์กลาง 1'' สำหรับจ่ายอากาศให้ดาวน์คัมเมอร์ทั้งสองด้าน การทำความร้อนให้อากาศใช้ขดลวดไฟฟ้าจำนวน 6 ชุด โดยมีกำลังไฟ

ฟ้าชุดละ 1.5 kW (รวมเท่ากับ 9 kW) การควบคุมอุณหภูมิใช้ชุดควบคุมอุณหภูมิแบบ P.I.D. สามารถควบคุมอุณหภูมิให้อยู่ในช่วง ± 1 °C จากค่าที่ตั้งไว้ การบันทึกอุณหภูมิใช้ data logger และ temperature indicator มีพิกัดความถูกต้อง ± 1 °C สำหรับการควบคุมอัตราการไหลของอากาศก่อนเข้าห้องอบแห้งซึ่งมีอุณหภูมิสูงใช้ orifice meterร่วมกับวาล์ว และสำหรับอากาศที่ออกจากห้องอบแห้งที่มีอุณหภูมิต่ำกว่า 90 °C จะวัดความเร็วอากาศด้วย hot wire anemometer มีความละเอียด ± 0.3 m/s ถ้าสูงกว่า 90 °C ใช้ Pitot – static tube ร่วมกับ U – tube manometer ในการควบคุมความเร็วรอบของมอเตอร์พัดลมใช้เครื่องปรับความเร็วรอบ (frequency inverter) การหาความชื้นเมล็ดข้าวเปลือกใช้วิธีชั่งนำหนักร่วมกับการให้ความร้อนในตู้อบที่อุณหภูมิ 103 °C เป็นเวลา 72 h สำหรับเครื่องชั่งน้ำหนักที่ใช้เป็นเครื่องชั่งน้ำหนักอิเลคทรอนิกส์ที่มีความละเอียด ± 0.0001 g ชั่งน้ำหนักได้สูงสุด 200 g สำหรับการหาปริมาณข้าวต้นเป็นไปตามมาตรฐานของสถาบันวิจัยข้าวและความขาวของข้าวใช้ kettmeter โดยในทุกเงื่อนไขการทดลองจะใช้ข้าวเปลือกจำนวน 6 kg โดยเมื่อใส่ลงในห้องอบแห้งแล้วจะได้ความสูงเบดประมาณ 0.72 m

6.3. ผลการทดลองและวิจารณ์

จากการทดลองพบว่าการถ่ายเทมวลหรือความชื้นไม่ได้เกิดขึ้นเฉพาะในบริเวณสเปาต์เท่านั้นแต่ขึ้นในบริเวณดาวน์คัมเมอร์ด้วยที่เปอร์เซ็นต์ของอากาศที่ไหลเข้าดาวน์คัมเมอร์ 20% และ 30% การที่ความชื้นและอุณหภูมิของข้าวเปลือกลดลงขณะที่เคลื่อนตัวในดาวน์คัมเมอร์เป็นผลมาจากปรากฏการณ์ evaporative cooling การเปลี่ยนแปลงความชื้นและเวลาพบว่ามีความสัมพันธ์เชิงเส้น อัตราการไหลของอากาศในดาวน์คัมเมอร์และอุณหภูมิอบแห้งมีผลอย่างมากต่อการลดลงของความชื้นข้าวเปลือกโดยเฉพาะที่ 30% และ150 °C อุณหภูมิอบแห้ง ปริมาณอากาศที่ไหลเข้าดาวน์คัมเมอร์และความชื้นเริ่มต้นส่งผลโดยตรงต่อค่าปริมาณข้าวต้น (HRY) และความชื้นวิกฤตความแตกต่างระหว่างค่าความชื้นเริ่มต้นและความชื้นวิกฤตที่ปริมาณข้าวต้นสัมพัทธ์ 100±5% มีค่าอยู่ระหว่าง 4.5-8.0 % d.b. โดยขึ้นอยู่กับเงื่อนไขการอบแห้ง ค่าความแตกต่างนี้จะเพิ่มขึ้นเมื่อความชื้นเริ่มต้นสูงขึ้นและจะลดลงเมื่ออุณหภูมิอบแห้งและปริมาณอากาศที่ไหลเข้าดาวน์คัมเมอร์มีค่าสูงขึ้น ในด้านของอุตสาหกรรมโรงสีข้าวจากผลการทดลองของค่าปริมาณข้าวต้นทำให้สรุปได้ว่าในการจัดการกับการอบแห้งข้าวเปลือกชื้นควรจะแบ่งการอบแห้งออกเป็นสองขั้นตอนซึ่งจะเป็นวิธีการที่เหมาะสมและให้ผลลัพธ์ที่ดี สุดท้ายจากการเปรียบเทียบกับเทคนิคฟลูอิไดซ์เบด พบว่าข้อดีของเทคนิค สเปาเต็ดเบดที่เหนือกว่าเทคนิคฟลูอิไดซ์เบดคือการเพิ่มขึ้นของอัตราการอบแห้งจำเพาะ(กิโลกรัมน้ำระเหยต่อชั่วโมงต่อลูกบาศ์กเมตรห้องอบแห้ง) และปริมาณข้าวต้น ในด้านของการสิ้นเปลืองพลังงานเครื่องอบแห้งสเปาเต็ดเบดจะด้อยกว่าเครื่องอบแห้งฟลูอิไดซ์เบดในกรณีอบแห้งข้าวเปลือกที่มีความชื้นสูงแต่ผลลัพธ์จะกลับกันในกรณีอบแห้งข้าวเปลือกที่มีความชื้นต่ำ ค่า

SEC_{th} ของเครื่องอบแห้งสเปาเต็ดเบดอยู่ระหว่าง 5.5-5.7 MJ/kg water evap โดยค่า SEC_{th} จะไม่เปลี่ยนไปตามความชื้นที่ลดลงและเวลาอบแห้งที่เพิ่มขึ้น

6.4. สรุปผลการทดลอง

6.4.1. มีการถ่ายเทมวล (ความชื้น) เกิดขึ้นภายในดาวน์คัมเมอร์ทุกเงื่อนไขของปริมาณอากาศที่เข้าดาวน์คัมเมอร์ แต่การถ่ายเทมวลเกิดจากปรากฏการณ์ evaporative cooling ไม่ใช่การอบแห้ง ซึ่งเป็นปรากฏการณ์ที่ทำให้ความชื้นและอุณหภูมิของข้าวเปลือกลดลงขณะที่เคลื่อนตัวในดาวน์คัมเมอร์

6.4.2. ความสัมพันธ์ระหว่างความชื้นเมล็ดข้าวเปลือกกับเวลาในการอบแห้งประมาณได้ว่าอยู่ในรูปความสัมพันธ์เชิงเส้น สำหรับทุกเงื่อนไขการทดลองนั่นคือปริมาณอากาศที่เข้าดาวน์คัมเมอร์ไม่มีอิทธิพลต่อ Drying curve characteristic

6.4.3. ปริมาณอากาศไหลเข้าดาวน์คัมเมอร์จะส่งผลโดยตรงกับอัตราการอบแห้งซึ่งเป็นผลรวมของการลดความชื้นในบริเวณสเปาต์และดาวน์คัมเมอร์

6.4.4. เงื่อนไขการอบแห้งได้แก่ อุณหภูมิอบแห้ง ปริมาณอากาศเข้าดาวน์คัมเมอร์และความชื้นเริ่มต้นส่งผลอย่างมากต่อค่าความชื้นวิกฤตและปริมาณข้าวต้น ถึงแม้ว่าการอบแห้งที่อุณหภูมิสูงและมีอากาศไหลเข้าดาวน์คัมเมอร์มากจะช่วยเพิ่มอัตรากา รอบแห้งแต่จะส่งผลเสียต่อค่าความชื้นวิกฤตและปริมาณข้าวต้น

6.4.5 เมื่อพิจารณาในด้านคุณภาพข้าวหลังการขัดสี การแบ่งการอบแห้งออกเป็นสองขั้นตอน น่าจะเป็นวิธีการที่เหมาะสมและให้ผลลัพธ์ที่ดีในการอบแห้งข้าวเปลือกโดยเทคนิคสเปาเต็ดเบด

6.4.6. เมื่อเปรียบเทียบกับการอบแห้งแบบฟลูอิไดซ์เบดพบว่าการอบแห้งข้าวเปลือกโดยเทคนิคสเปาเต็ดเบดให้ผลดีกว่ามากในด้านคุณภาพข้าวหลังการขัดสี ข้อดีอีกประการของเทคนิคการอบแห้งแบบสเปาเต็ดเบดที่เหนือกว่าการอบแห้งแบบฟลูอิไดซ์เบดคืออัตราการอบแห้งจำเพาะ (kg water evap $h^{-1}m^{3}$)สูงกว่า ในด้านการใช้พลังงานพบว่าค่า SEC_{th} ของเครื่องอบแห้งสเปาเต็ดเบดจะมีค่าอยู่ประมาณ 5.5-5.7 MJ/kg water evap.ซึ่งมากกว่าการอบแห้งแบบฟลูอิไดซ์เบดที่มีค่าอยู่ที่ระหว่าง 2.5-4.0 MJ/kg water evap

6.5 ข้อเสนอแนะ

สร้างและทดสอบเครื่องต้นแบบของเครื่องอบแห้งสเปาเต็ดเบดแบบต่อเนื่องในระดับอุตสาหกรรมโดยใช้ข้อมูลที่ได้จากการทดลองในห้องปฏิบัติการเป็นแนวทางในการออกแบบ

คำหลัก : การอบแห้ง คุณภาพข้าวหลังการขัดสี ความขาว ความสิ้นเปลืองพลังงานจำเพาะ เครื่องอบแห้ง ปริมาณข้าวต้น ฟลูอิไดซ์เบด

Abstract

Project Code: TRG4580085

Project Title: High Temperature Spouted Bed Paddy Drying With Varied Downcomer Airflows And Moisture Content: Effect On Drying Kinetics, Critical Moisture Content, and milling Quality

Investigators:

Investigators		Organization
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Project Period: 1 July 2002 – 30 June 2004

Objectives:

1. To investigate the effects of introducing air through downcomer regions on drying kinetics which is expected to promote intensive drying without any change of dryer volume
2. To study the impact of drying conditions such as drying temperatures, downcomer airflow and initial moisture content on physical properties of rice after milling process
3. To determine suitable strategy for drying paddy by spouted bed technique analyzing from the experimental results of drying kinetics and milling quality and finally
4. To compare spouted bed paddy drying with fluidized bed paddy drying of works involving

Methodology:

Spouted bed drying was studied in a two-dimensional spouted bed batch dryer as shown in Fig.1 and using paddy as tested material. The dryer comprised of a vertical rectangular chamber with a tempered glass window fitted to the front to permit visualization of grain flow pattern and a slant base chamber with an angle of 60°. The overall dimensions are 80 cm in width, 8.4 cm in depth and 120 cm in height. To investigate what drying kinetics and milling quality in terms of head rice yield and whiteness are going on

when distributing air downcomer regions, hot air was distributed at the bottom of slant base chamber through three air inlets namely a central rectangular air inlet serving for spout region with 3 cm in width and 8.4 cm.

Air was heated up by six of electric heaters with a capacity of 1.5 kW for each (9kW in total).The inlet air temperatures were automatically controlled by PID. Temperature controller with an accuracy of $\pm 1^{o}$C. Temperatures of system were measured by data logger and temperature indicator with an accuracy of $\pm 1^{o}$C connected to thermocouple type K. Air flow rates with high temperature were regulated by orifice meter cooperating with manual valves. For air recycled with temperature under 90^{o}C, air velocity was measured by hot wire anemometer with an accuracy of $\pm$ 0.3 m/s and for that with temperature above under 90^{o}C, Pitot-static tube with U-tube manometer was used. A 2.2 kW variable frequency inverter was used to regulate blower motor speed to attain desirable airflow rate which could be able to sustain stability of spouting behavior even in case of sharing much of hot air to downcomer regions. In order to determine moisture content of paddy, each sample of 20g paddy were measured by electronic balance with an accuracy of 0.0001g and drying it in hot air oven at 103^{o}C for 72 hours. Paddy of 6 kg which created bed height of 72 cm was filled into drying chamber for each experiment, and its color was measured by a Kett digital whiteness meter which was calibrated with a white color reference.

Results and Dicussion:

It was found that moisture transfer did not only occur in spout region but it also took place in downcomer region in particular for 20 and 30% downcomer airflow. Moisture and paddy temperature dropped as grain downward moving in downcomer was resulted from a present of evaporative cooling phenomenon. The characterization of drying curves regardless of any drying conditions could be described by nearly linear relationships between moisture content and time. Downcomer airflow and drying temperature were found to significantly influence effective moisture reduction with the highest downcomer airflow of 30% and temperature of 150^{o}C giving rise to the highest effective moisture reduction. Drying temperature, downcomer airflow and initial moisture content also had strongly effects on HRY and critical moisture content. The difference in moisture content between initial and critical moisture contents according to $100\pm 5\%$ relative HRY varied between 4.5 to 8.0 points (%d.b.) depended upon drying conditions. These numbers would increase as increase of initial moisture content and decease as increase of drying temperature and downcomer airflow. No significant effect on color was evident during testing period. Relating the HRY to strategy of spouted bed paddy drying in this way it indicated that a properly management of two-stages drying system could be a suitable and attractive alternative for rice mill industrial. Finally, the comparison between spouted bed and fluidized bed paddy drying exhibited that spouted bed had the advantages over fluidized bed in enhancing specific drying rate (kg water evap.$h^{-1}m^{-3}$) and improving the HRY. In aspect of energy consumption spouted bed was not efficient as fluidized bed in case of drying paddy with high moisture content but the contrary result would be obtained for low moisture content. The SEC_{th} of spouted bed was 5.5-5.7 MJ/kg water evap. and it was almost the same and not varied with decreased moisture content or drying time.

Conclusions:

1. Moisture decrease in spouted bed drying was a combination of moisture reduction in both spout and downcomer regions. Despite conventional convective drying as took place in spout, evaporative cooling phenomenon was believed a cause of moisture as well as bed temperature dropped along downward movement of paddy in downcomer.
2. Drying curves regardless to any drying temperature and downcomer airflow were characterized by nearly linear relationships between moisture content and time.
3. Downcomer airflow had showed an important effect in the effective moisture reduction defined as a combination of moisture reduction in spout and downcomer regions in the way that it increased as increasing downcomer airflow.
4. Drying conditions such as drying temperature, amount of downcomer airflow and initial moisture content had also significantly influenced critical moisture content and HRY. Even high drying temperature and introducing downcomer airflow enhanced moisture reduction but they had adverse effects on critical moisture content and HRY.
5. From a product quality point of view, two-stages drying (as well as incorporating with tempering process in-between may be necessary) seem to be a suitable strategy for spouted bed paddy drying system.
6. As compared spouted bed paddy drying in present study with fluidized bed paddy drying in concerned literatures, it was found that spouted bed presented much

better potential of preserving product quality in terms of HRY than that of fluidized bed. Another advantage of spouted bed over fluidized bed was higher specific drying rates (kg water evap.$h^{-1}m^{-3}$) than that of fluidized bed. Finally, SEC_{th} of spouted bed were in the range 5.5-5.7 MJ/kg water evap. which was higher than that of fluidized bed which was in the range of 2.5-4.0 MJ/kg water evap.

Recommendation:

To further study, an industrial-scale prototype of continuous spouted bed paddy dryer should be designed, constructed based on lab-scale experimental result and tested

Keywords: Dehydration; Dryer; Fluidized bed; Head rice yield; Product quality; Rice mill; Rough rice; Spouting; Thermal energy consumption; Whiteness.

เนื้อหางานวิจัย

HIGH TEMPERATURE SPOUTBED PADDY DRYING WITH VARIOUS DOWNCOMER AIRFLOW AND MOISTURE CONTENT: EFFECTS ON DRYING KINETICS, CRITICAL MOISTURE CONTENT AND MILLING QUALITY

INTRODUCTION

The combining of two hydrodynamics features i.e. pneumatic transport which was accompanied by intensive heat and mass transfers and moving bed transport which gave a chance for moisture relaxation and this functioned as tempering process are a main feature of spouted bed technique. An overall spouted bed technique was reviewed by Pallai et al.[1] and its design principle will be found in the article by Passo et al.[2] A two-dimensional spouted bed dryer firstly was proposed by Mujumdar[3] in order to overcome scaling up limitation of the conventional cylindrical-conical spouted bed. Kalwar et al.[4] and Karwar and Raghavan[5,6] later used it with draft plates for studying of soybean, wheat, corns and shelled corn drying. They found that kinetics drying models of those cereal grains were in good agreement with Page's equation which constant drying rate period did not distinctly exist. On the contrary, experimental results experienced by Wetchakama et al.[7], Ngugen[8], Ngugen et al.[9] and recent work of Wiriyaumpaiwong et al.[10] were found that nearly linear moisture and time relationships were good in describing drying characteristic. This could be explained by interaction between heat and mass transfer mechanisms in spout and downcomer regions that was demonstrated by simulation results of batch corn spouted bed drying as reported by Madhiyanon et al.[18]. The effect of bed height on effective moisture diffusion coefficient and drying rate was investigated by Tulasidus et al.[11] in the way that they increased as bed height decreased. This was resulted by shorter cycle time with a consequent of enhancing intensive heat transfer period in spout region. The drying characteristics were also reported by other literatures [12-17] however, quality of products after drying has been received less attention in these literatures although it is very important and usually employed in appraising the success or failure of grain drying system.

Recently, there was an attempt to introduce spouted bed drying technique to rice mill industrial by developing an industrial-scale prototype of continuous spouted bed paddy dryer based on scaling up two-dimensional spouted bed dryer as done by Madhiyanon et al.[19]. The prototype displayed a maximum capacity of 3550 kg /h. and thermal energy consumption of 3.5-7.0 MJ/kg water evap. according with 140-160^{o}C drying temperatures and 0.6-0.7 fraction of air recycled and, no serious loss in milling quality was observed during theirs experiment. However, the prototype had not much succeeded in moisture reduction due to insufficient dryer length. Madhiyanon et al.[20] also developed a mathematical model of continuous spouted bed dryer which theirs simulation resulted could predict very well in drying kinetics of an industrial-scale prototype of continuous spouted bed paddy dryer.

However, after evaluating experimental results of Madhiyanon[19] it was believed that continuous spouted bed paddy dryer has not been ready for positioning itself among other convention dryers or fluidized bed paddy dryer that are now popularly used in Thai rice mill industrials. There are three main questions about spouted bed paddy drying which has not been answered i.e

1) how to maximize drying capacity in terms of drying rate per unit volume of dryer and any way of accelerating drying rate, are there any serious effects on milling?

2) If dryer length is extended to increase mean residence time which results in more moisture reduction than that of a prototype achieved, what have any adverse effects on milling quality and finally

3) what strategies should be suitable for managing moist paddy with a variety of moisture content. The data of milling quality of paddy dried by spouted bed technique was rarely found in works concerning, only Ngugen et al.[9] reported that theirs a triangular spouted bed dryer could continuously reduce paddy moisture content to around 18% d.b. with the satisfaction of head rice yield regardless of high drying temperature up to 160°C. However, geometry of both of a triangular and an industrial-scale prototype of continuous spouted bed dryers were quite different particularly in bed height which that of triangular spouted bed dryer was about 5 meters and this was considerably much more than that of a prototype of continuous spouted bed dryers which was only 0.85 meter thus, milling quality results obtaining from that triangular spouted bed dryer can not be used as a guideline to predict that would be obtained from a prototype of a continuous spouted bed dryer.

THE MAIN OBJECTIVES OF THIS STUDY

1) To investigate the effects of introducing air through downcomer regions on drying kinetics which is expected to promote intensive drying without any change of dryer volume
2) To study the impact of drying conditions such as drying temperatures, downcomer airflow and initial moisture content on physical properties of rice after milling process
3) To determine suitable strategy for drying paddy by spouted bed technique analyzing from the experimental results of drying kinetics and milling quality and finally
4) To compare spouted bed paddy drying with fluidized bed paddy drying of works involving

MATERIALS AND METHODS

1. Materials

Spouted bed drying was studied in a two-dimensional spouted bed batch dryer as shown in Fig.1 and using paddy as tested material. The dryer comprised of a vertical rectangular chamber with a tempered glass window fitted to the front to permit visualization of grain flow pattern and a slant base chamber with an angle of 60°. Two draft plates with 90 cm in height were centrally installed which each draft plate was 3.7 cm distant apart from each other. The overall dimensions are 80 cm in width, 8.4 cm in depth and 120 cm in height. To investigate what drying kinetics and milling quality in terms of head rice yield and whiteness are going on when distributing air downcomer regions, hot air was distributed at the bottom of slant base chamber through three air inlets namely a central rectangular air inlet serving for spout region with 3 cm in width and 8.4 cm in depth and two of round air inlets for downcomer regions with 2.5 cm in diameter for each.

Air was heated up by six of electric heaters with a capacity of 1.5 kW for each (9kW in total).The inlet air temperatures were automatically controlled by PID. temperature controller with an accuracy of ±1°C. Temperatures of system were measured by data logger and temperature indicator with an accuracy of ±1°C connected to thermocouple type K. Air flow rates with high temperature were regulated by orifice meter cooperating with manual valves. For air recycled with temperature under 90°C, air velocity was measured by hot wire anemometer with an accuracy of ± 0.3 m/s and for that with temperature above under 90°C, Pitot-static tube with U-tube manometer was used. A 2.2 kW variable frequency inverter was used to regulate blower motor speed to attain desirable airflow rate which could be able to sustain stability of spouting behavior even in case of sharing much of hot air to downcomer regions. A three-phase kilowatt hour meter was used to measured heater energy usage.

2. Experiment Set-Up

One variety of long grain rough rice namely Suphanburi-1 which contains high amylase content of 27% (Tirawanichakul et al.[21]) provided by the National Research Center, Thailand was selected as tested material. Its moisture content was prepared by rewetting and keeping it in a cold storage at a temperature range of 4-6°C for 7 days. During cold storage period paddies were mixed thoroughly once a time in each day to make sure the uniformity of moisture. By preliminary studying it was found that grain velocity was impacted and varied according to different fraction of downcomer airflow to total airflow which could cause either positive or negative results on drying kinetics. Therefore, to eliminate the influence of different grain velocity accompanied by different air flowing through downcomer regions, the entrance height (see Fig. 1) was adjusted from one experiment to others to minimized variation of grain velocities. Measuring grain velocity was done by flow visualization and a stop watch.

The paddy samples of each condition were collected every 2-3 minutes time interval for moisture content, milling qualities and energy consumption evaluations. Especially for determining moisture variation in downcomer region, samples were taken at distance of 23 and 63 cm above air distributor. Total of sample taken from a dryer for each experiment was restricted to not more than 5% of initial hold-up (6kg) to make sure that process mechanism was not disturbed or deviated by sample collecting therefore, several experiments were done for each condition.

3. Experimental Conditions

Paddy of 6 kg which created bed height of 72 cm was filled into drying chamber for each experiment. The inlet air temperatures were set up at 110, 130 and 150°C. Total air mass flow rate of all experiments was held constant at around 0.052 kg/s and some of it was divided and sending to downcomer regions. The percentage of downcomer airflow ((mass flow rate of downcomer air / total mass flow rate of air) x 100%) were controlled at 0 (no downcomer air), 20 and 30%, respectively. Fractions of air recycled were set up within the range of 0.75 to 0.80. Besides studying the effects of downcomer airflow and drying temperature, the effect of initial moisture content on critical moisture content (that was considered as the lowest moisture content could be reduced before grain damages) and energy consumption was also studied. Thus, paddy was rewetted until reaching variety desirable levels that were in the rage of 18-35% d.b.

4. Physical Properties

In order to determine moisture content of paddy, each sample of 20g paddy were measured by electronic balance with an accuracy of 0.0001g and drying it in hot air oven at 103^{o}C for 72 hours. Before determining qualities of paddy in terms of head rice yield and whiteness, paddy samples taken at each time step were dried under room conditions for 2 weeks or until its moisture content reduced to around 16% d.b. Then each paddy sample of 125 g was shelled by Satake Rubber Roll husk, polished by Satake Rice Polisher and graded by Satake Grader, respectively. Finally, its color was measured by a Kett digital whiteness meter which was calibrated with a white color reference.

RESULTS AND DISCUSSION

All experiments were carried out corresponding to drying temperature of 110, 130, and 150 ^{o}C which were varied from one experiment to the other. To investigate the effect of downcomer airflow on drying kinetics, the downcomer airflow of 0, 20, and 30% (amount of downcomer airflow / total airflow x 100%) were regulated for each drying temperature level.

1. The Variation of Air and Grain Temperatures

All temperatures within the system were measured at the locations as shown on Fig.1. The experimental results showed that even using the varieties in drying temperatures with the same downcomer airflow, air and grain temperatures variation presented similar trend. The experiments carried under 130 ^{o}C drying temperature were risen for an example to show the influence of downcomer airflow on temperature changing within the system as presented in Fig. 2(a-c). It was obviously seen that temperature difference between inlet and exit air temperatures (curves 1 and 3) was nearly constant through out drying period which was not general behavior as that of other drying techniques that exit air temperature gradually approaches to inlet air temperature when drying is continuously going on. This was attributed to a distinct feature of spouted bed drying that drying was almost in constant drying rate period[7-10, 18] and consequence of nearly constant heat given by the hot air to grain to evaporate water inside grain. In additional, Fig. 2(a-c) also showed that temperature difference between inlet and exit air temperatures on the other hand, represented for amount of heat consumed for moisture removal became more incase of high downcomer airflow than that of lower downcomer airflow. This in lined with the experimental results of high moisture removed in accordance with high downcomer airflow.

It should be noted that with simulation results reported by Madhiyanon et al.[18] indicated that air flowing through the downcomer would approach to thermal equilibrium with grains at only a few centimeters upstream from the air inlet due to low mass ratio of air to grain in the downcomer. Thus, temperatures measured inside downcomer bed in this current study should present the value of grain temperatures at the relative bed height. Fig. 2(a-c) showed that paddy temperatures decreased around 2-5°C during its downstream movement displayed by shifting of curve 5 (0.65 m upstream from the central air inlet) to curve 7 (0.12 m bed height). The hypothesis to explain this evident was that there was a presence of evaporative cooling phenomenon (instead of conventional drying process) during paddy traveling in downcomer. This would be confirmed by the experimental results of moisture reduction inside downcomer region and this will be more discussed in the next section. Finally, the effect of downcomer airflow on grain temperature was observed that more downcomer airflow was introduced, paddy at the bottom of bed had higher temperatures (curve 7) and bringing them closed to temperatures of paddy at the middle (curve 6) however, they were still below the temperatures at the top(curve 5). Further more, it was also displayed that that high grain temperature concerning with high downcomer airflow directly relates to the corresponding drying rate and this will be further discussed in latter section.

2. Moisture Reduction in the Downcomer Region

As earlier work of Madhiyanon et al.[18] presented simulation results which indicated that moisture reduction of grains did not only occurred in the spout region but also occurred in the downcomer region due to air-leakage from the central inlet to downcomer, this was proofed by the present study. As shown in Fig. 3(a-f) corresponding to experiments allowing air penetrating to downcomer (0, 20 and 30% downcomer airflow) indicated that moisture of paddy in downcomer had been reduced around 0.2 to 0.7 point (or %d.b.) from beginning moisture of downcomer period for each trip of downstream movement distance of 0.4 m (see Fig.1 for locations of sample taking). The results also presented that in case of 20 and 30% downcomer airflow offered more moisture reduction than that case of no downcomer airflow (0%) (comparing between Figs.3a and 3f, Figs. 3b and 3d). However, in overview it was found that operating drying under 20 and 30% downcomer airflow did not give any significantly different of moisture reduction. This was attributed to moisture transfer mechanism was internally controlled by moisture diffusion rather than external surface convective mass transfer. It was interesting to note that moisture reduction in downcomer was considerably taken place by “evaporative cooling phenomena” not conventional drying. Since downcomer airflow, which having low mass compared to mass of grain, had not enough energy to evaporate moisture from paddy particularly, it approached to thermal equilibrium condition with paddy[18] therefore, decreasing in moisture in downcomer should be resulted from evaporative cooling phenomenon rather than conventional drying mechanism by hot air media. This was displayed as earlier described that temperature of paddy decreased during moving downward in downcomer, it could be explained that because heat accumulating inside paddy which performed as internal generating heat was used to evaporate water at paddy surface and then water was picked up by the air uniformly distributed through downcomer which consequently causing paddy cooled down. However, it was noticeable that for experiments that there was no intention to introduce air through downcomer (0% downcomer airflow), there was uncertainty about moisture reduction values as shown in Fig. 3(a-b). This probably may because moisture differences between top and bottom of downcomer in case of 0% downcomer airflow should be relatively less compared to that case of 20 and 30% downcomer airflow so only slight error in moisture measurement was able to deviate moisture data, not alike to case of 20 and 30% downcomer airflow which band of moisture differences were wide so a little bit error in measurement could not counteract experimental data.

3. Drying Curve Characteristic

Fig. 4(a-c) exhibited drying characteristics and the effects of drying temperatures on the effective moisture reduction (combination of moisture reduction in the spout and downcomer regions). All experiments regardless of varieties of drying temperature and downcomer airflow conditions were found that most of drying curves had a similarity of drying characteristic which the correlations between moisture content and time were almost nearly linear relationships[23-24]. This was also found by the previous works[7-10, 18] and it should be resulted from an assistance of moisture relaxation during downcomer motion period due to grains having enough time for immigrating water from the inside to outside of grain kernel. This should facilitate water vaporization when grains transited to the spout region where grain exposed to relatively high temperature and velocity of air. This drying kinetics of spouted bed extremely distinguishes from fluidized bed technique which moisture content and drying time relation is in exponential correlation[23-24]. It was clearly seen that drying temperature significantly influenced drying rate in the way that drying rate increased with increase of drying temperature. Further more, in comparing between Figs. 4(a), 4(b) and 4(c) it was obviously seen that drying rate directly related to drying temperature in the direction that rapidly decreasing in moisture was achieved by applying high temperature.

4. Grain Velocity in the Downcomer Region

In all experiments, total mass flow rates of air was held constant at 0.053 kg/s and in order to neglect the effect of grain velocity on drying kinetics, there were attempts to set up grain velocities to minimize its fluctuation corresponding to a variety of downcomer airflow by adjusting entrance height. However, the best could be done in our experiments was that maximum deviation in grain velocity from each to other did not exceed 15%. By visualizing paddy velocities, it were found that the lowest paddy velocity was 0.7 cm/s which existed for 0% downcomer airflow whereas it was nearly 1.0 cm/s for the rest of downcomer airflow (20 and 30%). By visualization observing, it could be seen that if air was allowed to flow upward through downcomer it would facilitate in circulation of grain at the bottom and hence grain stacked above could easily move downward to replace the one below.

5. Influence of Downcomer Airflow on the Effective Moisture Reduction

Utilizing air flowing through dowcomer would give an advantage of achieving high effective moisture reduction which was a combination of moisture reduction in the spout and downcomer regions as appeared in Fig. 5(a-c). Drying kinetics involving to any drying temperatures had a similarity trend which moisture decreasing was directly proportional to downcomer airflow in the way that 30% downcomer airflow considerably promoted the highest effective moisture reduction and it would stepped down for 20 and 0% downcomer airflow, respectively. However, as mentioned before that moisture reduction rates in the downcomer were nearly the same with not regarding to either using high or low downcomer airflow. Therefore, this reflected that extra moisture reduction between 0, 20 and 30% downcomer airflow should gain from drying mechanism in the spout region. This was attributed to interaction of heat and mass transfer between spout and downcomer regions[18,21] such that higher airflow in the downcomer resulted in grain being hotter (referring to Fig. 2(a-c) it was clearly seen that temperature data corresponding to curve no 7. of 30% downcomer airflow was higher than that of 0% downcomer airflow) which resulted in grain accompanying with higher moisture diffusion coefficient and this would help in accelerating moisture evaporation when grain transited from downcomer region to a subsequent spout region.

6. Milling Quality

Figs. 6-8 exhibited the experimental results of milling quality in which relative head rice yield (HRY) changing along moisture content decreased regarding to drying temperature of 110, 130 and 150^{o}C. At the beginning of drying period relative HRY increased and thereafter it began decreasing along moisture content decreasing. Because at the beginning paddy comprising of sufficiently high temperature and moisture content which were considerable suitable for initiating gelatinization process, therefore partially gelatinization was expected to be formed at the kernel rice and making its starch was more sufficient strength to resist stresses developed within paddy kernel during drying process. But whenever moisture was further continuously reduced, much more stresses developed by steep moisture gradient dominated gelatinization effect and resulted in grain breakage during milling process. In this study, initial moisture contents were classified in three levels namely low (17-21% d.b.), medium (24-28% d.b.) and high (31-35% d.b.) moisture contents. More discussions on milling qualities were presented as the following topics.

7. The effects of drying temperatures and downcomer airflow with a variety of initial moisture contents on critical moisture content and HRY

For drying paddy with temperature of 110^{o}C, paddy with low initial moisture content of 21% d.b. could be safely dried until moisture content reached to 14% d.b. which was considerably safe for storage without any paddy damages (Fig. 6(a)). In case of medium initial moisture content of 27-28% d.b. (Fig. 6(b)) it was found that in order to preserved paddy quality, paddy should not be continuously dried to moisture level lower than critical moisture content (defined as moisture content accompanying with 100±5% relative HRY) of 21% d.b.

For drying temperature of 130^{o}C, moisture content could be reduced from 18 % d.b. (low moisture content) to 13% d.b. without any effecting milling quality as shown on Fig.7(a). However, as shown on Fig. 7(b) that paddy with medium initial moisture content of 27-28% d.b. could not be dried lower than critical moisture content of 22% d.b. in case of 0 % downcomer airflow and critical moisture content would raise up in case of 20 and 30 % downcomer airflow. Table 1 will give more numerical details.

Fig. 8(a) presented results of HRY involving to drying temperature of 150^{o}C and medium initial moisture content of 24-25% d.b. The results showed that critical moisture content was about 19.5-20.5 % d.b. and critical moisture content in case of 30% downcomer airflow was less than that of 0% downcomer airflow around 1% d.b. For drying paddy with high moisture content of 31-32% as shown on Fig. 8(b), critical moisture content was around 25-26% d.b.

8. The relation between drying temperatures, initial moisture contents, downcomer airflow and maximum moisture reduction

As above describing was also presented by the results in Table 1.

- The results displayed that by applying temperature of 110^{o}C for drying paddy with low and medium initial moisture content of 21-27% d.b., it was able to reduce moisture content around 6-7 points from its initial moisture content.

- For drying temperature of 130^{o}C with low and medium initial moisture content of 17-27% d.b., reduction in moisture content was around 4.0-6.5 points while it could accomplished around 8 points for high initial moisture content of 35% d.b.

- For the highest drying temperature of 150^{o}C with medium and high initial moisture content of 24-32% d.b. resulted in moisture reduction of about 4.5-6.0 points.

In overview, it could be concluded that drying conditions such as drying temperature, amount of downcomer airflow and initial moisture content also had influences on HRY. Figs. 6(b) and 7(b) according to temperature of 110 and 130^{o}C under the same initial moisture content indicated that spouted bed drying carried under higher temperature was responsible for higher critical moisture content. On the other hand, at the same final moisture content, HRY corresponding to high drying temperature was less than that corresponding to low drying temperature. Data in Figs. 6-8 also presented the influence of downcomer airflow on HRY in the direction that 0% downcomer airflow gave the best results of relative HRY while 30% downcomer airflow gave the worst. It was seen that critical moisture content regarding to 0% downcomer airflow was around 1% d.b. lagging behind that of 30% downcomer airflow. This was mainly due to paddies were not flexible enough to resist stresses rapidly promoted by progressively accelerating in moisture removal in case of high downcomer airflow. It was noticeable that amount of moisture content could be reduced before touching level of critical moisture content directly related to initial moisture content. Finally, higher initial moisture content, larger difference in moisture content between initial and critical moisture contents was obtained before grain damages. In comparing between Figs. 7(a) and 7(b), 8(a) and 8(b) as well as data in Table 1 would give clearer picture.

9. The effect of grain temperature on HRY

In additional, Fig. 6(c) also displayed the variation of bed temperature, which representing for grain temperature due to thermal equilibrium condition, and it pointed out that the breakage of paddy possibly should not be caused by too high temperatures of paddy since temperatures in accordance with relative HRY was less than 100% were in the range of 65-70^{o}C which was relatively less compared to that of paddy dried by fluidized bed which grain temperatures were in the range of 75-95^{o}C while HRY was still maintained (Poomsa-ad et al.[22]). Again this confirmed that paddy damage was mainly due to steep moisture gradient inside paddy.

10. Whiteness

Finally besides the HRY, the whiteness was also an important issue which was used for concerning the paddy quality. The experimental results indicated that no serious loss in whiteness was found in these experiments as shown in Figs. 6-8 and Table 1.

11. Thermal Energy Consumption

The experimental results as shown in Table 2 indicated that thermal specific energy consumption (SEC_{th}) in accordance with any downcomer airflow and drying temperatures slightly differed from each to other. The data in Table 2 displayed that using temperature of 110, 130 and 150^{o}C incorporating with 75-80% recirculated airflow for drying paddy from moisture content of 31% d.b. to approximate 15-20% d.b., SEC_{th} were in the rage of 5-6 MJ/kg water evap. These values of SEC_{th} were inline with 3.5-7.0 MJ/kg water evap. of an industrial-scale prototype of continuous spouted bed paddy dryer [19] and they were reasonable and relatively comparable to other conventional commercial dryers. Moreover, due to nearly constant drying rate characteristic of spouted bed technique thus SEC_{th} is almost the same for any drying time interval or decreased moisture content. Therefore, in aspect of energy utilization spouted bed dryer is able to compete to other commercial dryers especially for the second stage of paddy drying which paddy has relative low moisture content that is normally dried with high energy consumption.

12. Strategy for Spouted Bed Drying Technique

As above evaluation of milling quality, it appeared that it was not able to dry paddy from high moisture content to a level that was considerably safe for storage in one stage drying and this is also true for fluidized bed drying or other conventional drying. Therefore, two-stages drying (as well as coupling with tempering process in-between may be necessary) should be considerably suitable for spouted bed paddy drying. For moist paddy with high moisture content such as 30% d.b., which is in the range of post harvested moisture content (28-32% d.b.), temperature of 130 or 150^{o}C without downcomer airflow can be used for the first stage drying with a consequent of approximate moisture content of 24 % d.b at the end of the first stage (interpreting form value of difference in moisture between initial and critical moisture content as shown in Table 1). For the second stage, temperature of 110°C incorporating with 0-30% downcomer airflow would give final moisture content around 17-18% d.b. that was close to safety storage level and when sending paddy to a final subsequent process of ambient air ventilation in order to cooling paddy, moisture was easily reduced to 15-16% d.b. before storage. Therefore, a properly managed spouted bed paddy drying could be an attractive alternative for rice mill industrial.

THE COMPARISON BETWEEN SPOUTED BED and FLUIDIZED BED TECHNICQUES

1. Milling quality comparison

Comparing in drying capacity and milling quality between spouted bed and fluidized bed techniques should be simultaneously criticized since excellence in drying capacity is no meaning if product quality after drying is not acceptable. In aspect of milling quality after drying of paddy, Poomsa-ad et al.[22] reported that drying paddy with high initial moisture content of 30-35% d.b. according to high drying temperatures of 110, 130, 150 and 170°C in a single stage of a lab-scale fluidized bed dryer they could accomplish more than 80% of relative HRY if final moisture content was above 25% d.b. corresponding to grain temperatures in the rage of 70-90°C. In a similarity drying condition as present study, spouted bed drying was able to reduce moisture content from 31-35% d.b. to 25-27% d.b. with an achievement of 100±5% relative HRY (Figs. 7(c), 8(b) and Table 1).

For drying paddy with medium moisture content, study of Poomsa-ad et al.[22] stated that continuously drying paddy from 25 to 20% d.b. would caused seriously low relative HRY which was lower than 40% unless incorporating with a subsequent tempering for 30 minutes which could bring relative HRY up to more than 60%. Whilst spouted bed drying could accomplish 100±5% relative HRY in reducing moisture content from 24 to 19.5% d.b. and 20 to 14% d.b. without tempering process (Figs. 6(a), 8(a) and Table 1). Poomsa-ad et al.[22] also highlighted that to achieve high HRY under high drying temperature in one pass of fluidized drying corresponding to grain temperature not over than 100°C, paddy should not be reduced lower than 22.5% d.b. and a subsequent tempering for 30 minutes was strongly recommended to preserve HRY.

As above discussion, it was clearly seen that starting drying with high initial moisture content (30-35% d.b.) spouted bed was able to reach lower critical moisture content than fluidized bed on the other word; spouted bed could reach the same final moisture content in a single stage drying as fluidized bed but achieving higher HRY than fluidized bed. For moisture content not over 25% d.b. spouted bed offered more points (%d.b.) decreasing from beginning and better HRY.

2. Drying capacity comparison

In aspect of drying capacity, specific drying rate which defined as drying rate per unit volume of drying chamber (kg water evap.$h^{-1}m^{-3}$) was used as an index to measure drying capability of dryer. Comparison of specific drying rate between both techniques was shown on Table 3. The dryer volume according to spouted bed was based on dimensional as shown on Fig. 1 and that according to fluidized bed drying was based on fluidized bed dryer studied by Tirawanichaku et al.[21] which dryer was in a cylindrical shape with 20 cm in diameter and 140 cm in height and, 1.9 kg of paddy corresponding of 10 cm static bed height was constantly held in theirs experimental. As seen on Table 3, if drying time was only considered to point out drying capability, it seemed that fluidized bed drying could reduce moisture substantially faster than spouted bed drying. However, volume of dryer and hold up (capability of holding amount of paddy for one batch of experimental) should be taken into account for justice comparison thus, specific drying rate was risen up as an indicator for this purpose.

Data in Table 3 showed that spouted bed drying had higher specific drying rate in all case of drying temperatures in particular that drying process carried under temperature of 110^oC, specific drying rate of spouted bed was higher than that of fluidized bed around 44%. For fluidized bed drying accompanying with temperature of 110^oC, the advantage of aggressive heat and mass transfer due to all time contacting of grain and air and well-mixing characteristic was counteracted by less driving force due to less temperature gradient between grain and air. Whilst in spite of all time exposing of grain to air, spouted bed allowed relaxation time (approximate 110 seconds for one cycle) in downcomer period which substantially helped in equalizing temperature within grain kernel. Thus, surface temperature of paddy at the end of downcomer period was not so high as just coming from spout region which led to enhancing heat transfer between paddy surface and air in spout region.

For temperature of 150^oC, spouted bed drying also offered better result in specific drying rate which was higher than that of fluidized bed about 19%. This could be explained that drying characteristic of fluidized bed was in Arrhenius or exponential form while nearly linear relationship was represented for spouted bed drying characteristic. Fluidized bed gave steep decreasing of moisture at the beginning of drying (accelerating in speed of drying) thereafter moisture gradually decreased (decelerating in speed of drying) while a special feature of spouted bed drying displayed that it gave nearly constant drying rate not regarding to any moisture decreased from initial moisture content. This made specific drying rate of spouted bed left behind that of fluidized bed at the beginning and in the remaining period it could catch up and finally overtake that of fluidized bed.

3. Thermal energy consumption comparison

Finally, thermal energy regarding to both techniques were compared. Because energy consumption of experimental results in lab-scale fluidized bed were not available so the records of thermal energy consumption of commercial fluidized bed dryer as reported by

Soponronnnarit et al.[25] (dryer with capacities of 2.5-5 tons/h and 5-10 tons/h) were used for this comparison. They summarized that drying paddy with initial moisture content varied between 26.0-30.6% d.b. and moisture contents were reduced to 21.0-23.0% d.b., SEC_{th} (specific thermal energy consumption) were in the range of 2.5-4.0 MJ/kg water evap. which was considerably relatively low as compared to conventional hot air dryer. However, in case of drying paddy with low initial moisture content such as 22.0% d.b. down to 20.1% d.b. SEC_{th} steep raised to 7.8 MJ/kg water evap. Data as shown on Table 2 exhibited that spouted bed could dry paddy from high initial moisture content i.e., 31.6-32.3 % d.b. down to around 20.1-22.5% d.b. in accordance with SEC_{th} of 5.5-5.7 MJ/kg water evap. Moreover, due to nearly constant drying rate characteristic of spouted bed technique thus SEC_{th} should be almost the same for any reduced moisture content. This appeared in Table 2 that it could reduce moisture content form 30.5-32.5 % d.b. to 15.5-17.8% d.b. with nearly the same SEC_{th} of 5.6 MJ/kg water evap. In additional, referring to data on Table 1 and the work done by Poomsa-ad et al.[22] presented the necessity for dividing drying process in to two-stages drying in order to reduce moisture close to safety storage level with simultaneously maintaining acceptable milling qualities for both drying techniques. Therefore, fluidized bed should consume less energy than spouted bed for the 1st stage drying but the converse result would be obtained for 2nd stage drying which normally starting drying with moisture content around 20.0-22.0% d.b

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CONCLUSIONS

The experimental study of paddy drying in a two-dimensional spouted bed batch dryer was conducted to investigate the effects of drying temperature, downcomer airflow and initial moisture content on drying kinetics, critical moisture content and product quality. The comparison between spouted bed and fluidized bed as well as proper strategy for spouted bed paddy drying was also discussed in this study. The following paragraphs are the conclusions of this study.

1. Moisture decrease in spouted bed drying was a combination of moisture reduction in both spout and downcomer regions. Despite conventional convective drying as took place in spout, evaporative cooling phenomenon was believed a cause of moisture as well as bed temperature dropped along downward movement of paddy in downcomer which corresponded to accumulating heat (inside grain) used for water vaporization. Moisture reduction in downcomer was around 0.2 to 0.7 points for each trip of 0.4 m downward movement. Introducing downcomer airflow substantially helped in moisture reduction in downcomer.
2. Drying curves regardless to any drying temperature and downcomer airflow were characterized by nearly linear relationships between moisture content and time. This was also reflected by almost constant difference of temperatures between inlet and exit air. Drying rate was strongly affected by drying temperature with it increased with increases of drying temperature.

3. Downcomer airflow had showed an important effect in the effective moisture reduction defined as a combination of moisture reduction in spout and downcomer regions in the way that it increased as increasing downcomer airflow.

4. Drying conditions such as drying temperature, amount of downcomer airflow and initial moisture content had also significantly influenced critical moisture content and HRY. Even high drying temperature and introducing downcomer airflow enhanced moisture reduction but they had adverse effects on critical moisture content and HRY. The difference in critical moisture content according to 0, 20 and 30% downcomer airflow was about 1% d.b. A gap between initial and critical moisture contents increased with increase of initial moisture content. Paddy with moisture content of 21-27% d.b. could be safely dried under temperature of 110^{o}C with an achievement of 6-7 points of moisture reduction (at 100±5% relative HRY). For drying temperature of 130^{o}C, paddy with moisture content of 17-27% d.b. could be dried with satisfactory of HRY if moisture reduction was within 4.0-6.5 points while 8.0 points was accomplished corresponding to initial moisture content of 35% d.b. Air temperature of 150^{o}C could also be used for drying paddy with moisture content of 24-32% d.b. as long as moisture reduction was in the range of 4.5-6.0 points. It was also observed that paddy breakage did not be resulted from too high grain temperature but it was probably affected by steep moisture gradient. Finally, there was no serious loss in the whiteness was observed in this study.

5. From a product quality point of view, two-stages drying (as well as incorporating with tempering process in-between may be necessary) seem to be a suitable strategy for spouted bed paddy drying system. Starting drying with temperature of 130 or 150^{o}C for the first stage follows by drying temperature of 110^{o}C for the second stage is possible.

As compared spouted bed paddy drying in present study with fluidized bed paddy drying in concerned literatures, it was found that for a single stage drying without a subsequent process of tempering and dealing with similar drying conditions, spouted bed presented much better potential of preserving product quality in terms of HRY than that of fluidized bed either in case of high or medium initial moisture content. Another advantage of spouted bed over fluidized bed was higher specific drying rates (kg water evap.$h^{-1}m^{-3}$) than that of fluidized bed around 19-44% for all case of drying temperatures. Finally, SEC_{th} of spouted bed were in the range 5.5-5.7 MJ/kg water evap. which was higher than that of fluidized bed which was in the range of 2.5-4.0 MJ/kg water evap. However, spouted bed could compete with fluidized bed where paddy with low moisture was dried since SEC_{th} of spouted bed was almost the same for any level of decreased moisture content.

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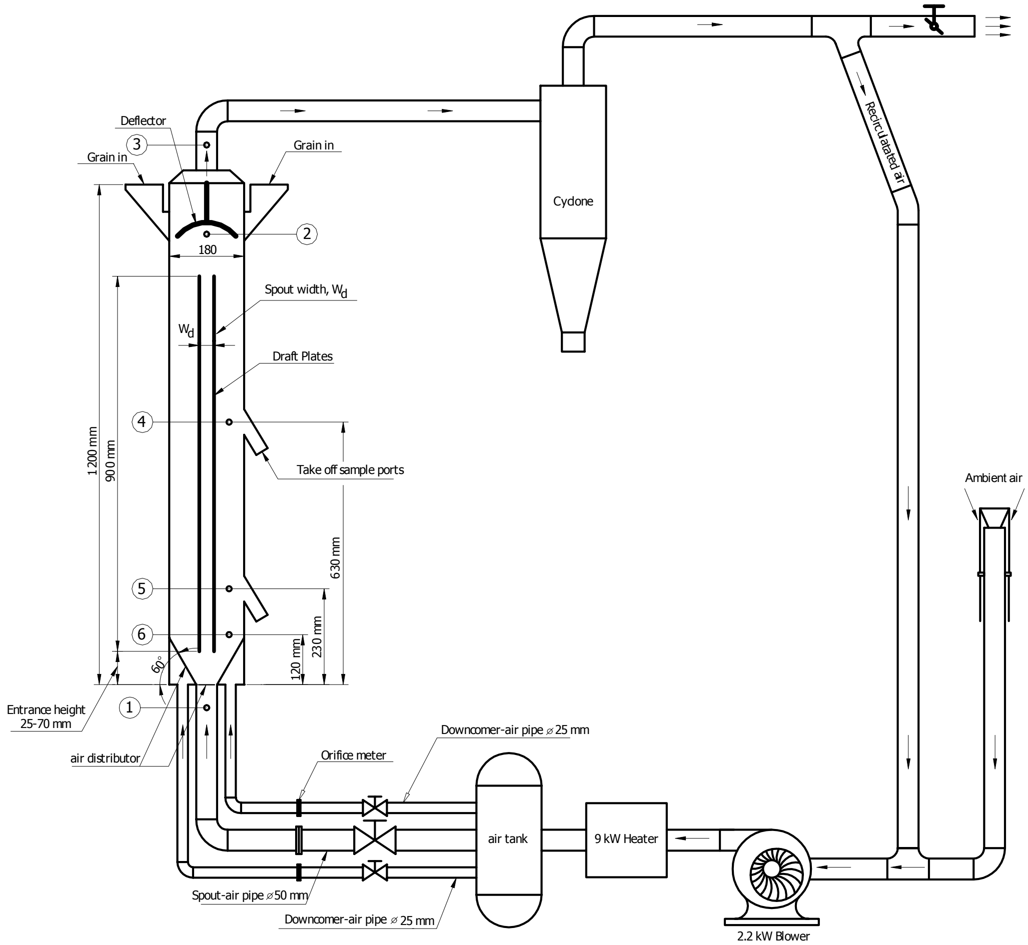
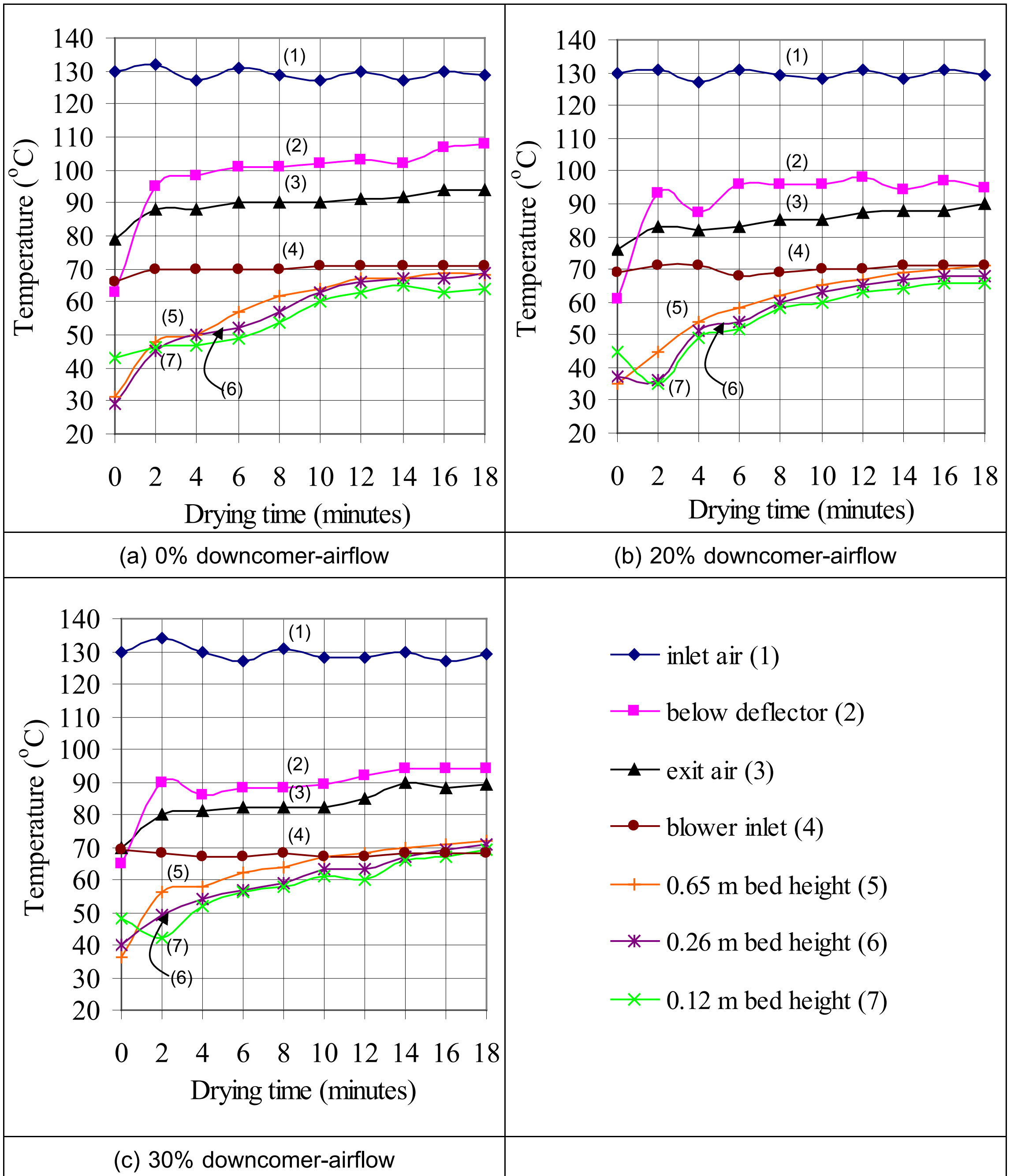


Figure 1. Schematic diagram of two-dimensional spouted bed dryer with various downcomer airflow and temperature measurement positions.

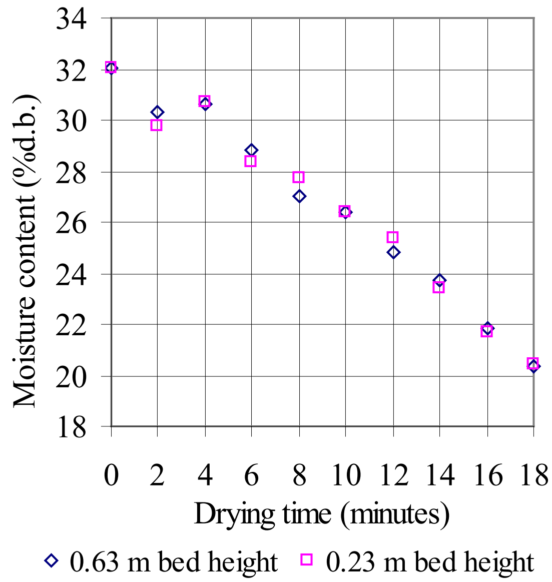


(a) 0% downcomer-airflow

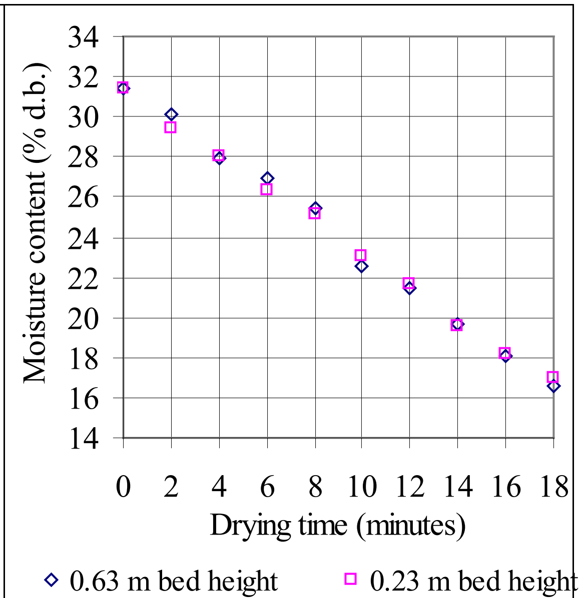
(b) 20% downcomer-airflow

(c) 30% downcomer-airflow

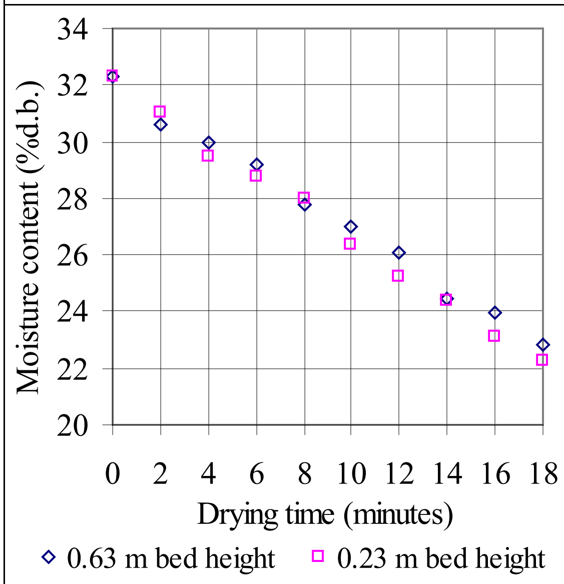
Figure 2. Variation of air and grain temperature within drying system according to percentage of downcomer-airflow (inlet temperature 130 °C)



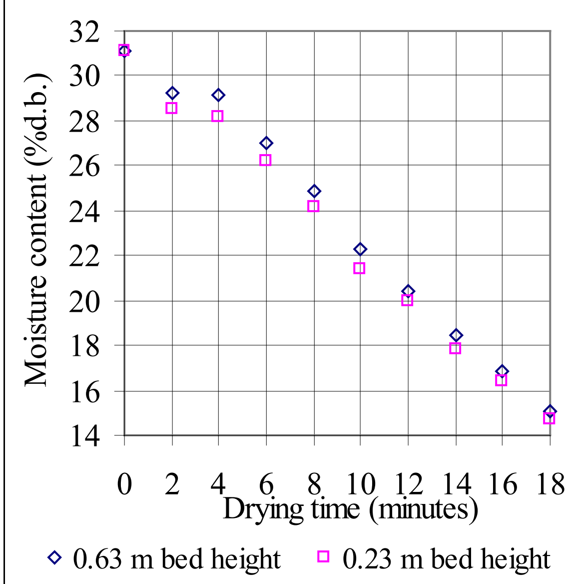
(a) inlet air temperature 130 °C; 0% of downcomer-airflow



(b) inlet air temperature 150 °C; 0% of downcomer-airflow

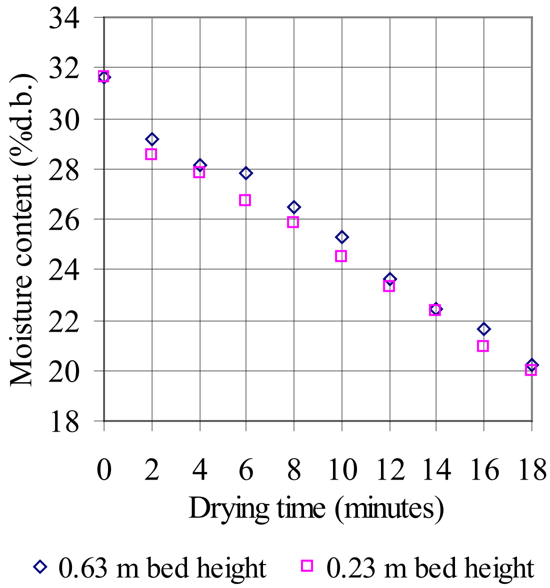


(c) inlet air temperature 110 °C; 20% of downcomer-airflow

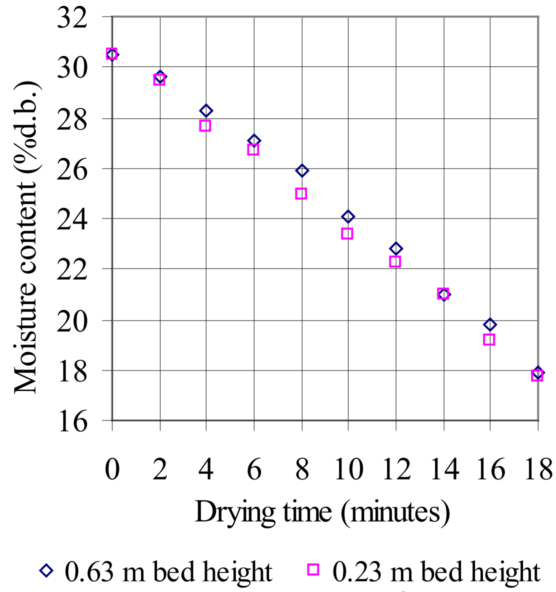


(d) inlet air temperature 150 °C; 20% of downcomer-airflow

Figure 3. The moisture reduction along bed height in downcomer region.

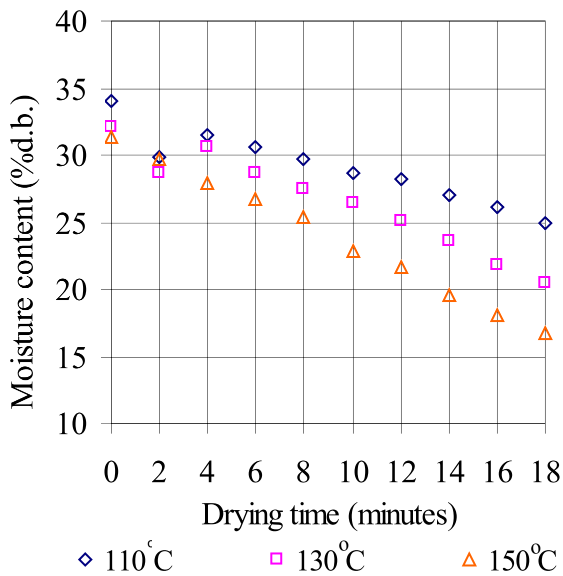


(e) inlet air temperature 110 °C; 30% of downcomer-airflow

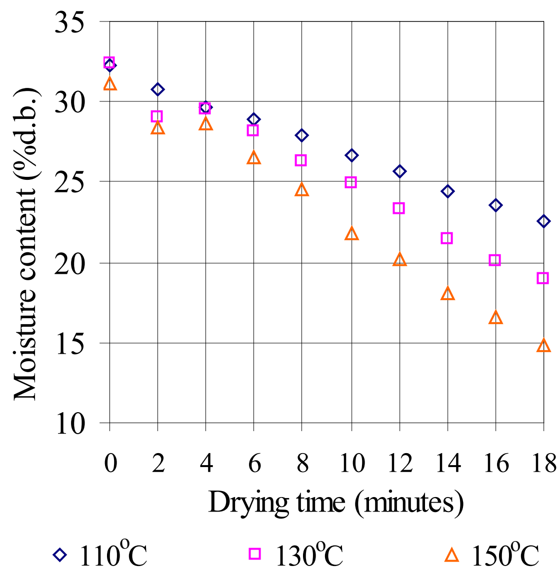


(f) inlet air temperature 130 °C; 30% of downcomer-airflow

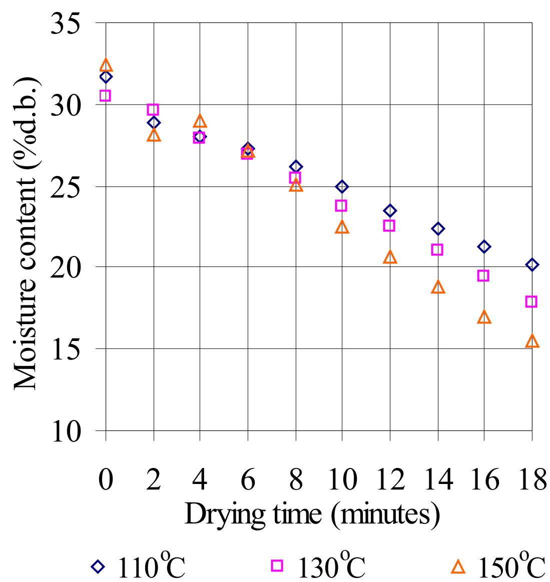
Figure 3. The moisture reduction along bed height in downcomer region (cont.).



(a) 0% of downcomer-airflow



(b) 20% of downcomer-airflow



(c) 30% of downcomer-airflow

Figure 4. Nearly linear characteristic of spouted bed drying regardless of drying conditions of temperature and percentage of downcomer-airflow.

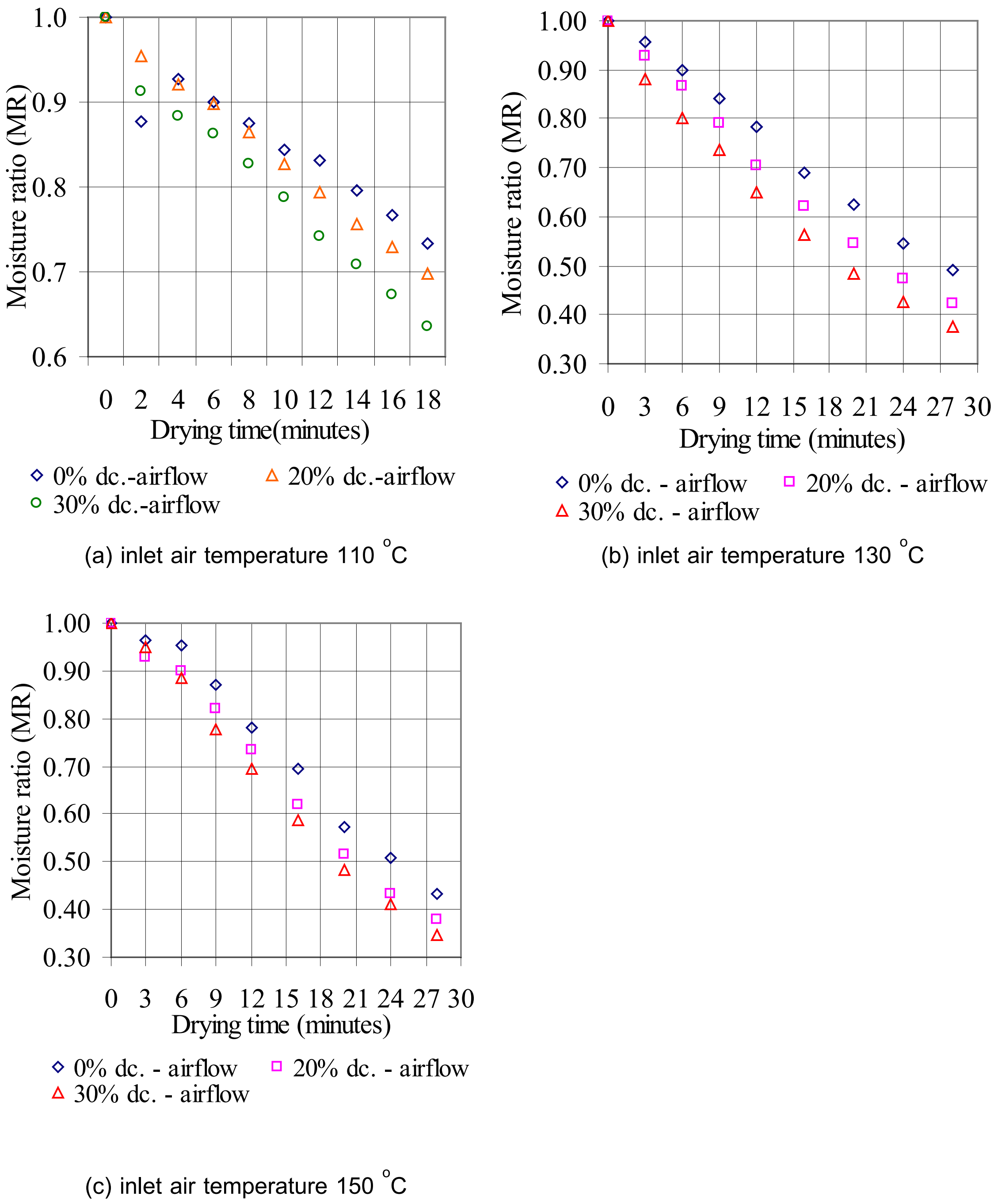
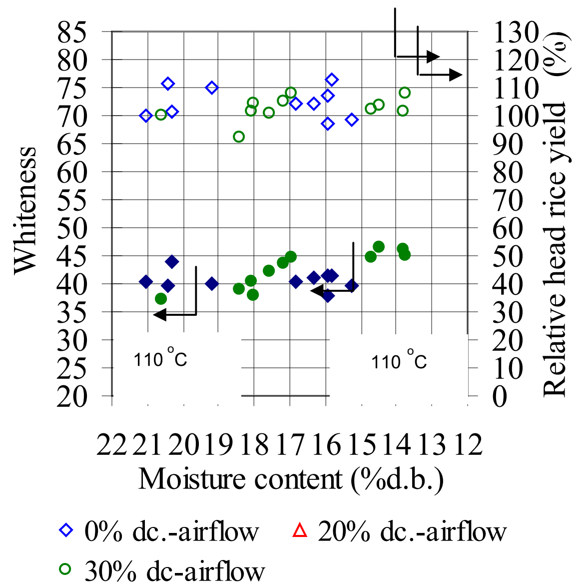
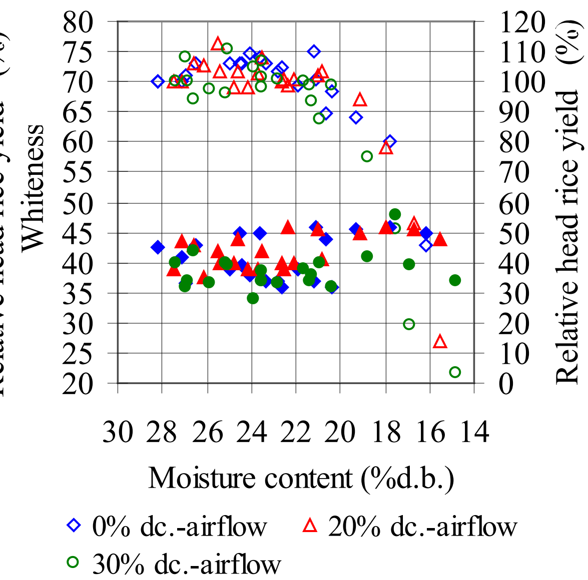


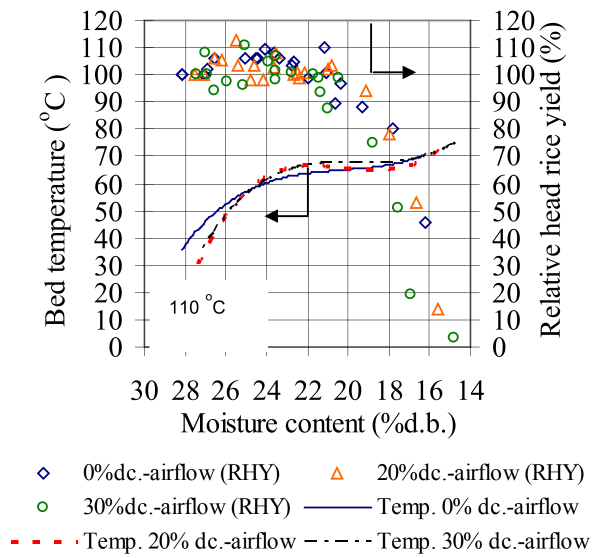
Figure 5. The effect of downcomer-airflow on the effective moisture reduction (dc. = downcomer)



(a) low initial moisture content, 20.5 and 21%d.b. (whiteness reference, 37 and 40)

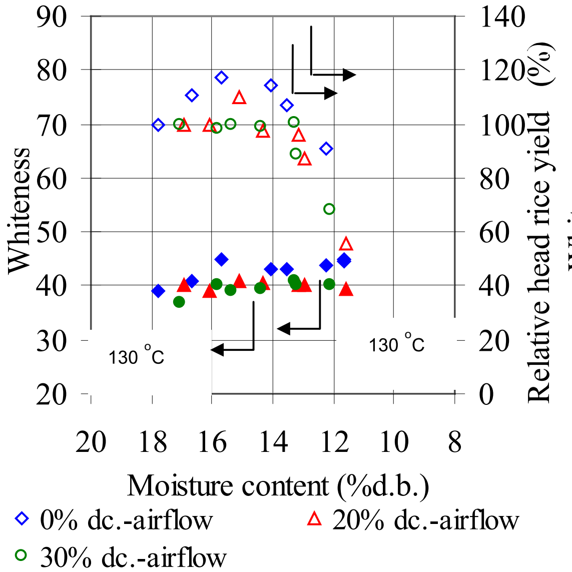


(b) medium initial moisture content, 27 and 28%d.b. (whiteness reference, 38 and 43)

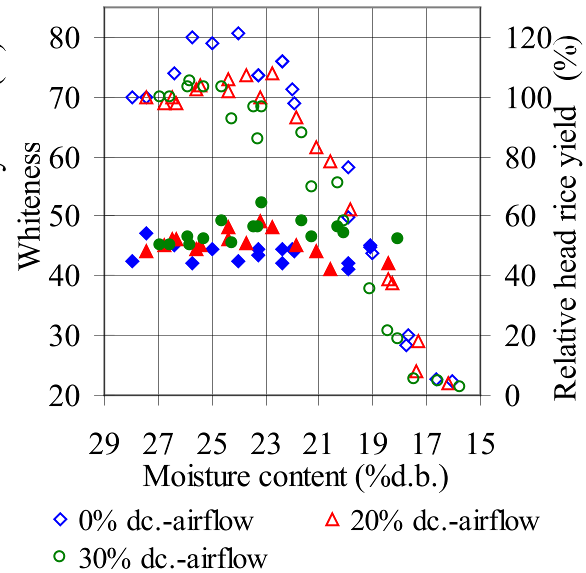


(c) replotting relative HRY as shown on figure 6(b) coupling with the variation of bed temperatures

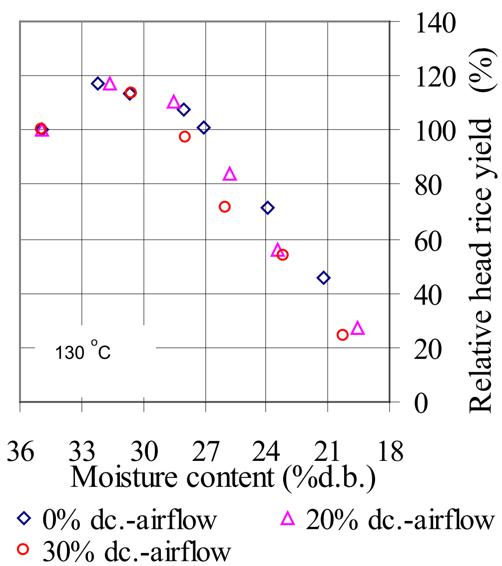
Figure 6. The variation of relative head rice yield and whiteness along moisture decreased according to a variety of initial moisture content and 110 °C drying temperature (dc.= downcomer).



(a) low initial moisture content, 18%d.b. (whiteness reference, 39)

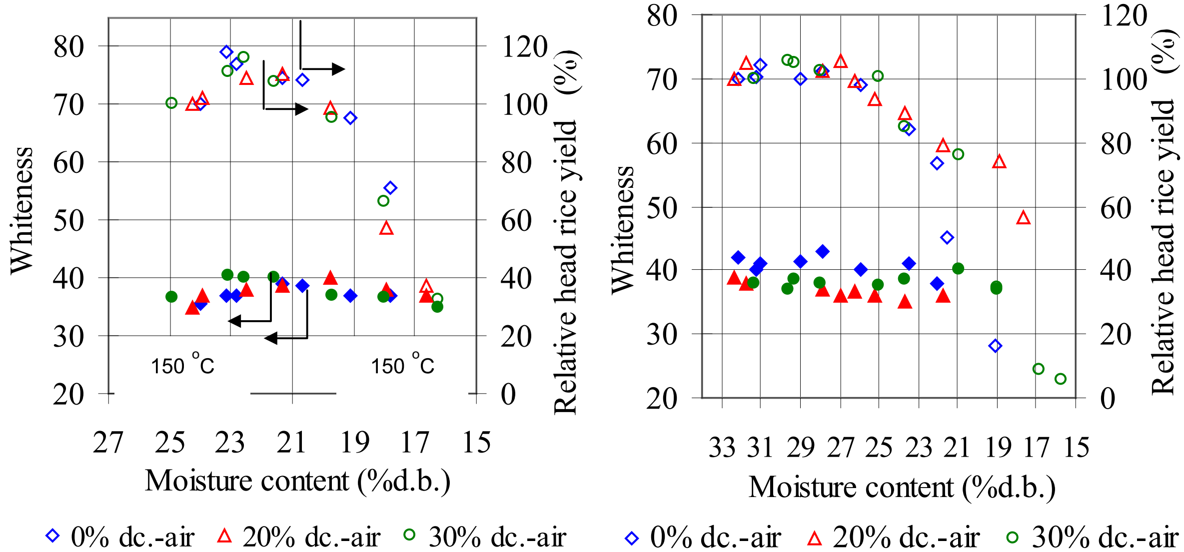


(b) medium initial moisture content, 26 and 27.5%d.b. (whiteness reference, 41 and 44)



(c) height initial moisture content, 35%d.b.

Figure 7. The variation of relative head rice yield and whiteness along moisture decreased according to a variety of initial moisture content with 130 °C drying temperature (dc.= downcomer).



(a) medium initial moisture content; 24 and 25%d.b. (whiteness reference; 35 and 37)

(b) height initial moisture content; 32%d.b. (whiteness reference; 38 and 42)

Figure 8. The variation of relative head rice yield and whiteness along moisture decreased according to a variety of initial moisture content with 130 °C drying temperature (dc.= downcomer).

ผลลัพธ์ที่ได้จากโครงการ

1. บทความตีพิมพ์ในวารสารภายในประเทศและต่างประเทศ

[1] Madhiyanon, T.; Soponronnarit, S.; Tia, W. High Temperature Spouted bed Paddy Drying With Various Downcomer Airflows And Moisture Content: Effects On Drying Kinetics, Critical Moisture Content And Milling Quality. Drying Technology - An International Journal **2004**,22(9)

[2] ฐานิตย์ เมธิยานนท์, สมชาติ โสภณรณฤทธิ์, การอบแห้งเมล็ดพืชที่อุณหภูมิสูงโดยเทคนิค สเปาเต็ดเบดที่สามารถปรับเปลี่ยนอัตราการไหลอากาศเข้าดาวน์คัมเมอร์ได้, การประชุมวิชาการเครือข่ายวิศวกรรมเครื่องกลแห่งประเทศไทยครั้งที่ 17

2. ผลลัพธ์จากการทดลองสามารถยืนยันได้ว่าเทคนิคการอบแห้งแบบสเปาเต็ดเบดสามารถที่จะพัฒนาไปสู่ระดับอุตสาหกรรมได้โดยพิจารณาจากผลของจลน์ศาสตร์การอบแห้ง คุณภาพข้าวหลังการขัดสี และการสิ้นเปลืองพลังงานซึ่งอยู่ในเกณฑ์ที่น่าพอใจ สามารถแข่งขันได้กับเครื่องอบแห้งฟลูอิไดซ์เบดและเครื่องอบแห้งแบบทั่วไป