



รายงานวิจัยฉบับสมบูรณ์

โครงการ: การผลิตความร้อนจากการเผาไหม้เชื้อเพลิงชีวมวล
โดยเทคนิคฟลูอิดไชน์เบดร่วมกับการฉีดอากาศแบบ
วอร์เทคโดยไม่ต้องผสมวัสดุเฉื่อยลงในเบด

โดย ผศ.ดร.ฐานิตย์ เมธิยานนท์ และคณะ

มิถุนายน 2550

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คณะผู้วิจัย

สังกัด

1. ผศ.ดร.ฐานิตย์ เมธิยานนท์

ม.เทคโนโลยีมหานคร

2. ศ.ดร.สมชาติ ไสภณรณฤทธิ์

มจร.

สนับสนุนโดยสำนักงานคณะกรรมการการอุดมศึกษา และสำนักงานกองทุนสนับสนุนการวิจัย
(ความเห็นในรายงานนี้เป็นของผู้วิจัย สกอ. และ สกว. ไม่จำเป็นต้องเห็นด้วยเสมอไป)

กิตติกรรมประกาศ

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ขอขอบคุณสำนักงานคณะกรรมการการอุดมศึกษา (สกอ.) และสำนักงานกองทุนสนับสนุนการวิจัย (สกว.) ที่ให้การสนับสนุนทุนวิจัย

1. รหัสโครงการ : MRG4880011
2. ชื่อโครงการ : การผลิตความร้อนจากการเผาไหม้เชื้อเพลิงชีวมวลโดยเทคนิคฟลูอิดไชน์เบด ร่วมกับการฉีดอากาศแบบบอร์เทค โดยไม่ต้องผสมวัสดุเฉื่อยลงในเบด

3. ชื่อนักวิจัย :

คณะผู้วิจัย

สังกัด

3.1. ผศ.ดร.ฐานิตย์ เมธิยานนท์

ม.เทคโนโลยีมหานคร

3.2. ศ.ดร.สมชาติ โสภณรณฤทธิ์

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6. เนื้อหางานวิจัย :

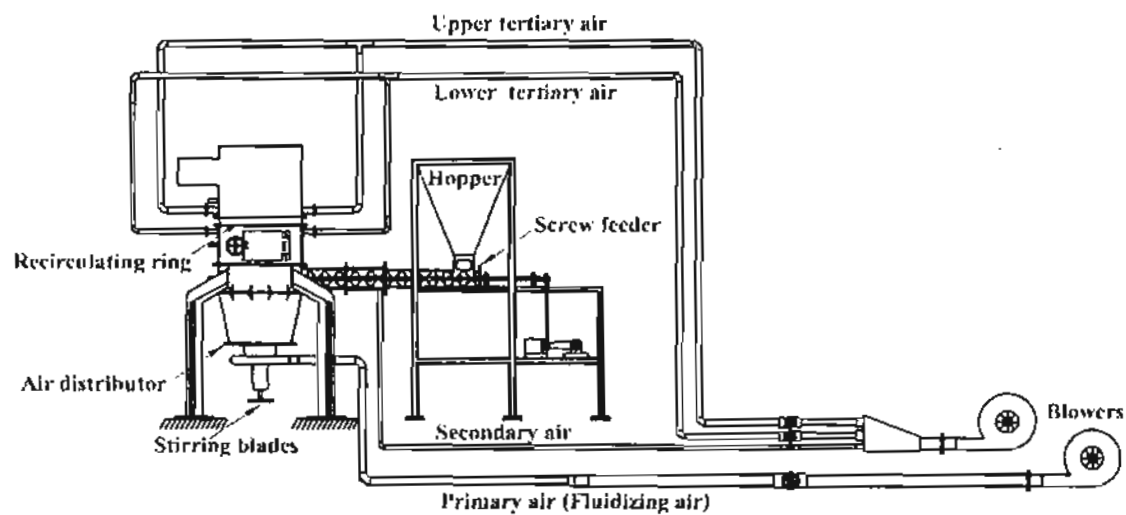
6.1. วัตถุประสงค์

- 6.1.1. ส่งเสริมการใช้เชื้อเพลิงชีวมวลเพื่อเป็นพลังงานทดแทนพลังงานจากเชื้อเพลิงฟอสซิลที่มีราคาสูงในปัจจุบันและต้องนำเข้าจากต่างประเทศ
- 6.1.2. พัฒนาเทคนิคการเผาไหม้เชื้อเพลิงชีวมวลในเตาเผาไหม้แบบฟลูอิดไชน์เบดเพื่อลดปัญหาการเกาะตัวของเชื้อเพลิงชีวมวลขณะเผาไหม้ และหาวิธีการการเพิ่มการหมุนเวียนของอนุภาคเชื้อเพลิงในห้องเผาไหม้ (เพื่อเพิ่มเวลาที่อนุภาคอยู่ในเตาเผาไหม้) โดยที่สัดส่วนความสูงต่อเส้นผ่านศูนย์กลางของเตาต้องมีค่าอยู่ในเกณฑ์ที่เหมาะสมต่อการพัฒนาไปสู่ภาคอุตสาหกรรมในอนาคต

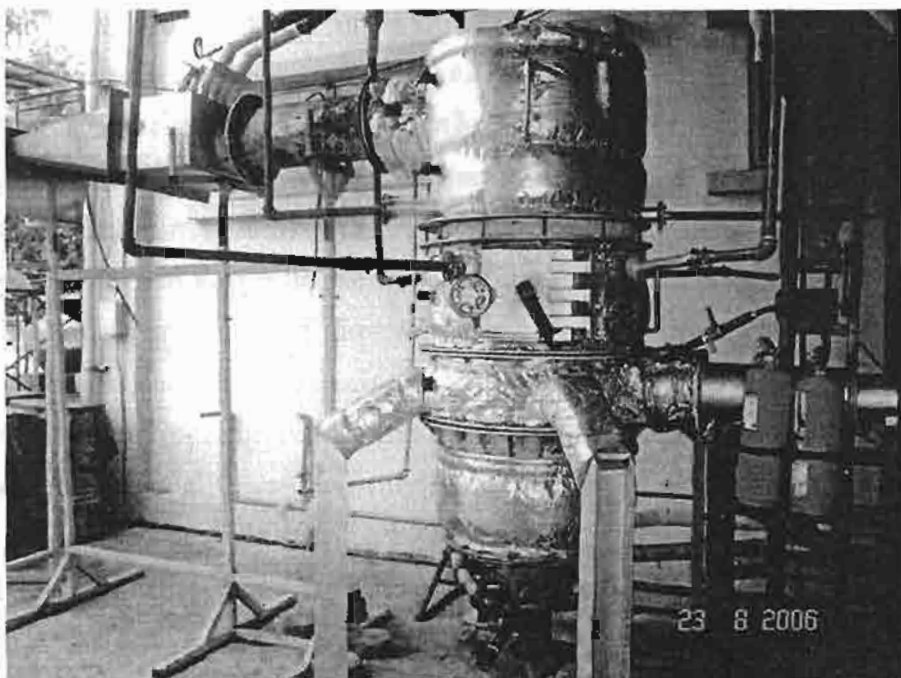
6.2. ระเบียบวิธีวิจัย

ในงานวิจัยนี้ ได้ออกแบบและพัฒนาเตาเผาไหม้ฟลูอิดไชน์เบดที่แบบห้องเผาไหม้สั้นซึ่งมีอัตราการผลิตความร้อน 250 kW_{th} ดังรูปที่ 1 โดยตัวเตาเผาไหม้จะแบ่งออกเป็นสองส่วนคือ 1) ส่วนที่เป็นทรงกระบอกซึ่งมีเส้นผ่านศูนย์กลาง 0.5 m สูง 0.97 m และ 2) ส่วนที่เป็นลักษณะกรวยหงายตัดยอดซึ่งมีขนาดเส้นผ่านศูนย์กลางที่ยอดกรวยตัด 0.3 m และมีความสูง 0.6 m ดังรูปที่ 2 ซึ่งส่วนกรวยนี้จะออกแบบไว้สำหรับรองรับเบดของซีเถ้าและอนุภาคเชื้อเพลิงที่มีขนาดใหญ่ นอกจากนี้ ภายในเตาเผาไหม้ส่วนที่เป็นทรงกระบอกยังติดตั้ง Recirculating ring โดยมีขนาดรูวงแหวน 0.3 m และติดตั้งที่ระดับ 1.13 m เหนือแผ่นกระจายอากาศ การติดตั้ง Recirculating ring จะทำให้ห้องเผาไหม้ถูกแบ่งออกเป็น 2 ห้อง คือ ห้องเผาไหม้ฟลูอิดไชน์เบด ซึ่งเป็นห้องเผาไหม้หลัก (ใต้ Recirculating ring) และห้องเผาไหม้รอง (เหนือ Recirculating ring) นอกจากนี้จะช่วยดักจับ

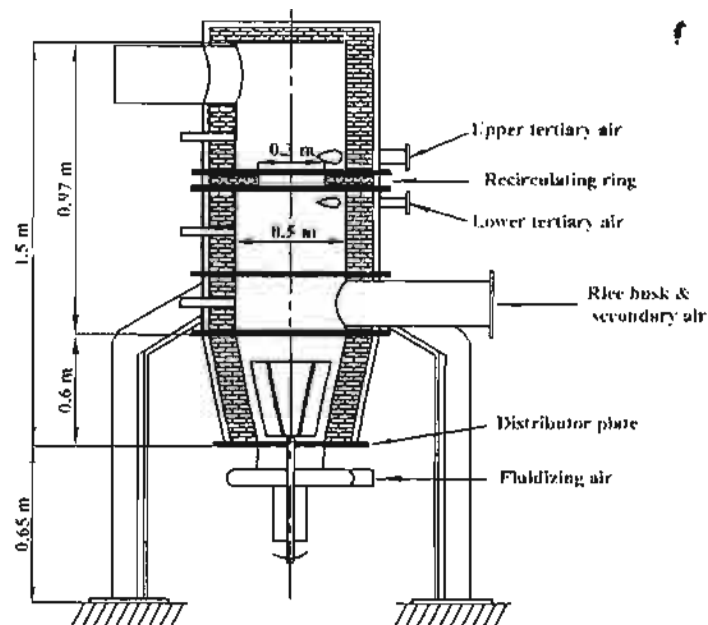
อนุภาคเชื้อเพลิงที่หลุดลอยไปกับแก๊สเผาไหม้ซึ่งมาจากห้องเผาไหม้หลัก เป็นผลให้เกิดการหมุนเวียนของอนุภาคเชื้อเพลิงภายในเบดที่เกิดฟลูอิดเซชัน



รูปที่ 1(ก) แสดงไดอะแกรมของเตาเผาไหม้ฟลูอิดไธด์แบบห้องเผาไหม้สันขนาด 250 kW_{th}



รูปที่ 1(ข) แสดงภาพถ่ายของเตาเผาไหม้ฟลูอิดไธด์แบบห้องเผาไหม้สันขนาด 250 kW_{th}

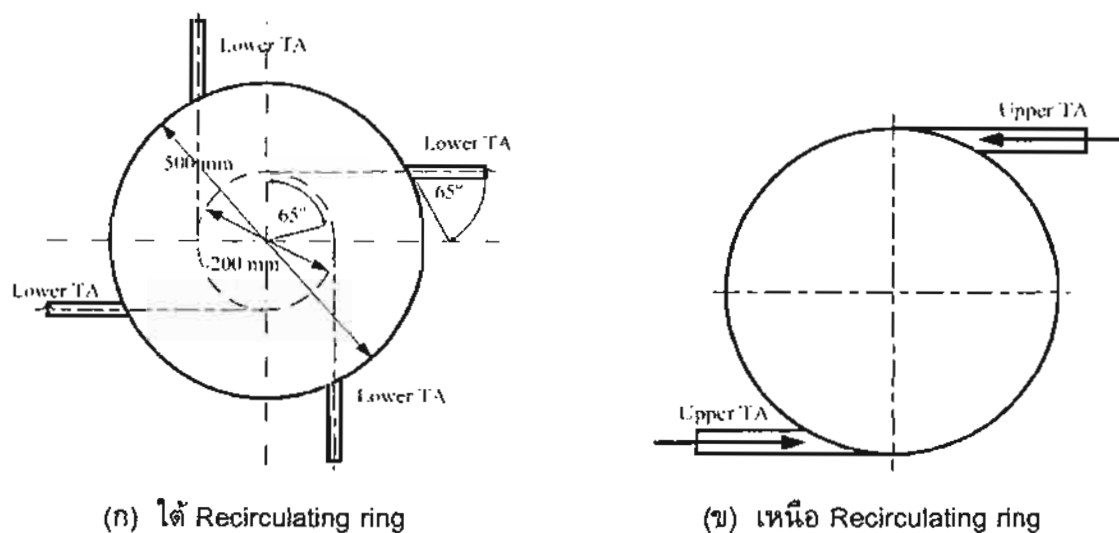


รูปที่ 2 แสดงภาพตัดของเตาเผาไหม้ฟลูอิดไรซ์เบดแบบห้องเผาไหม้สั้น

การป้อนแกลบเข้าสู่เตาเผาไหม้จะใช้สกรูลำเลียง ซึ่งควบคุมอัตราการป้อนด้วยการปรับความเร็วรอบของมอเตอร์ สำหรับการจ่ายอากาศส่วนที่หนึ่ง (อากาศที่ก่อให้เกิดฟลูอิดไรซ์ชัน) จะจ่ายด้วยพัดลมขนาด 2.2 kW อากาศส่วนที่สองจะจ่ายเข้าไปพร้อมกับเชื้อเพลิงเข้าสู่เบดเพื่อป้องกันการลุกไหม้ของไฟเข้าสู่ระบบป้อนเชื้อเพลิง อากาศส่วนที่สามจะใช้พัดลมขนาด 2.2 kW จ่ายที่ตำแหน่งเหนือ Recirculating ring และใต้ Recirculating ring โดยที่ตำแหน่งใต้ Recirculating ring (1.03 m เหนือแผ่นกระจายอากาศ) จะจ่ายผ่านหัวฉีด 4 หัว ซึ่งทำให้เกิดวงแหวนอากาศขนาดเส้นผ่านศูนย์กลาง 0.2 m ดังรูปที่ 3ก สำหรับอากาศส่วนที่สามเหนือ Recirculating ring จะจ่ายในลักษณะสัมผัสผนังเตาเผาไหม้ผ่านหัวฉีดอากาศ 2 หัว ซึ่งอยู่ตรงกันข้ามกันเพื่อกวาดให้อนุภาคที่ตกบน Recirculating ring ให้กลับลงในห้องเผาไหม้ใต้ Recirculating ring ดังรูปที่ 3ข นอกจากนี้เพื่อป้องกันการเกาะตัวของอนุภาคแกลบที่ก้นเตาเผาไหม้ ได้ติดตั้งใบกวาดซึ่งทำจากสแตนเลสและหล่อเย็นด้วยอากาศอยู่ภายในเบดที่แนวกึ่งกลางเตาเผาไหม้ ซึ่งจะหมุนด้วยความเร็ว 6 rpm

ในการทดลองนั้น การป้อนเชื้อเพลิงจะถูกควบคุมโดยชุดปรับความเร็วรอบมอเตอร์ การวัดความเร็วอากาศจะใช้หัววัด Hot wire (ความถูกต้อง $\pm 3\%$) ส่วนการวัดอุณหภูมิภายในเตาจะใช้เทอร์โมคัปเปิลชนิด K คู่กับชุดเก็บข้อมูล (data logger) ซึ่งมีความถูกต้อง $\pm 1^{\circ}\text{C}$ โดยตำแหน่งที่ทำการวัดคือ 0.6, 0.93, 1.33 และ 1.58 m เหนือแผ่นกระจายอากาศ นอกจากนี้ยังมีการวัดการ

กระจายอุณหภูมิตามแนวรัศมีของเตาเผาไหม้ในแต่ละระดับความสูงอีกด้วย ในการวัดแก๊สไอเสีย จะใช้เครื่องวิเคราะห์ Testo 350 XL ซึ่งติดตั้งเซลล์วัดแก๊ส O_2 , CO, NO และ NO_2 สำหรับการวิเคราะห์ปริมาณคาร์บอนที่ไม่เผาไหม้จะใช้เครื่องวิเคราะห์ Leco C-H-N-S ส่วนลักษณะของการเผาไหม้แบบฟลูอิดไคส์เบดจะทำการสังเกตอย่างใกล้ชิดผ่านช่องเปิดข้างผนังเตา



รูปที่ 3 ลักษณะการจ่ายอากาศส่วนที่สามเข้าสู่เตาเผาไหม้ที่ระดับต่างๆ •

การเริ่มต้นทดลองทำได้ง่าย ซึ่งไม่ต้องใช้เชื้อเพลิงอื่น เช่น แก๊สแอลพีจี (LPG) ในการเริ่มต้น โดยแกลบจะถูกใส่เข้าในเตาเผาไหม้ผ่านทางประตูเตาให้มีความสูงเบดประมาณ 20-30 cm เหนือแผ่นกระจายอากาศแล้วจึงทำการจุดแกลบที่ใส่ลงไป รอจนกระทั่งอุณหภูมิเบดสูงขึ้นประมาณ $450^{\circ}C$ แล้วจึงเพิ่มอัตราการป้อนเชื้อเพลิงไปยังค่าที่ต้องการและเปิดพัดลมจ่ายอากาศส่วนอื่น ๆ อย่างไรก็ตามไม่มีการใช้วัสดุเฉื่อยอื่น ๆ มาช่วยให้เกิดการเผาไหม้แบบฟลูอิดไคส์เบดแต่จะใช้ถ้ำของแกลบซึ่งเกิดระหว่างการเผาไหม้ (ซิลิกอน (SiO_2) $\approx 90\%$) ทำหน้าที่เป็นวัสดุเฉื่อย

ในการศึกษาจะทำการทดลองทั้งหมด 9 เงื่อนไข ซึ่ง 5 เงื่อนไขเป็นการศึกษาโดยปรับเปลี่ยนความเร็วของอากาศที่ก่อให้เกิดฟลูอิดไคส์เบดและคงอัตราป้อนแกลบ ส่วนอีก 4 เงื่อนไขเป็นการศึกษาภายใต้การทำงานไม่เต็มพิกัด โดยทำการปรับอัตราการป้อนเชื้อเพลิงแต่จะคงที่ปริมาณลมส่วนต่างๆ ไว้ เงื่อนไขการทดลองจะแสดงดังตารางที่ 1 นอกจากนี้ ยังมีการศึกษาการเผาไหม้แกลบร่วมกับถ่านหินบิทูมินัสเบื้องต้นอีก 3 เงื่อนไขด้วยกัน

ตารางที่ 1 แสดงเงื่อนไขการทดลองเผาไหม้เชื้อเพลิงแกลบ

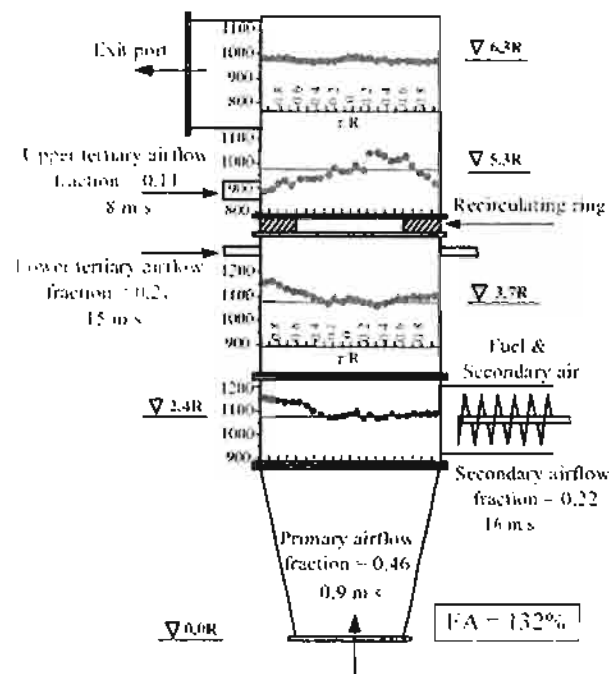
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Run Nos.	Primary air		Secondary air		Tertiary air				Rice husk feed rate (kg/h)	Excess air (%)	Air-fuel ratio
					Upper recirculating ring		Lower recirculating ring				
	Velocity (m/s)	Fraction (-)	Velocity (m/s)	Fraction (-)	Velocity (m/s)	Fraction (-)	Velocity (m/s)	Fraction (-)			
Effect of primary air											
1	0.5	0.33	16	0.27	8	0.14	15	0.26	66	83	8.32
2	0.8	0.44	16	0.23	8	0.11	15	0.22	66	119	9.98
3	0.9	0.46	16	0.22	8	0.11	15	0.21	66	132	10.56
4	1.2	0.54	16	0.19	8	0.10	15	0.18	66	164	12.01
5	1.4	0.57	16	0.17	8	0.10	15	0.16	66	174	12.47
Partial-load operational											
6	1.0	0.47	15.7	0.22	7.8	0.11	13.6	0.20	73	117	9.87
7	1.0	0.47	15.7	0.22	7.8	0.11	13.6	0.20	66	140	10.92
8	1.0	0.47	15.7	0.22	7.8	0.11	13.6	0.20	50	220	14.56
9	1.0	0.47	15.7	0.22	7.8	0.11	13.6	0.20	33	380	21.84

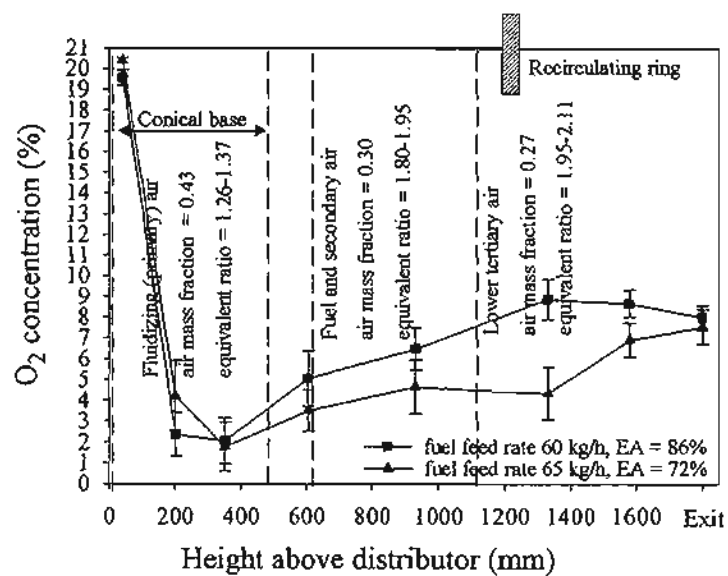
6.3. ผลการทดลองและวิจารณ์

จากการทดลองพบว่า การเผาไหม้ส่วนใหญ่เกิดขึ้นบริเวณใต้ Recirculating ring ในช่วงความสูง 0.6 m และ 0.93 m จากระดับแผ่นกระจายอากาศ นอกจากนี้ ยังพบว่าการกระจายตัวของอุณหภูมิในบริเวณนี้มีลักษณะเป็นไอโซเทอร์มอลเบด (isothermal bed) ดังรูปที่ 4 ซึ่งสะท้อนถึงการเผาไหม้แบบฟลูอิดไคส์เบด แสดงว่าเกิดการเผาไหม้แบบฟลูอิดไคส์เบดได้โดยไม่ต้องผสมวัสดุเฉื่อยลงในเบด ซึ่งสอดคล้องกับการสังเกตผ่านช่องเปิดข้างเตาเผาไหม้แล้วเห็นอนุภาคเชื้อเพลิงที่กำลังเผาไหม้ฟุ้งกระจายภายในเบดอย่างสม่ำเสมอ รวมทั้งสอดคล้องกับการลดลงของปริมาณออกซิเจนในแต่ละระดับความสูงของเตาเผาไหม้ ดังรูปที่ 5

การเพิ่มความเร็วของอากาศส่วนที่ก่อให้เกิดฟลูอิดไคส์เบดหรือการปรับอัตราการป้อนเชื้อเพลิง ส่งผลให้ปริมาณอากาศส่วนเกินมีค่าในช่วง 83-380% ซึ่งในช่วงความเร็วของอากาศส่วนที่ก่อให้เกิดฟลูอิดไคส์เบดและอัตราการป้อนเชื้อเพลิงในช่วง 0.5-1.4 m/s และ 33-73 kg/h โดยในทุกเงื่อนไขการทดลองมีอุณหภูมิเบดไม่เกิน 1200°C และมีประสิทธิภาพการเผาไหม้ (E_c) ในช่วง 95.6-99.8% ซึ่งคิดเป็นอัตราการผลิตความร้อน (I_c) ที่ 1.34-1.54 MW_{th}/m² การใช้ความเร็วของอากาศที่ก่อให้เกิดฟลูอิดไคส์เบดสูงถึง 1.4 m/s ซึ่งคิดเป็นอากาศส่วนเกิน 174% ส่งผลให้ E_c มีค่าค่อนข้างต่ำที่ 95.6% อย่างไรก็ตาม ภายใต้เงื่อนไขการทดลองปกติ (อัตราการป้อนแกลบ 66-73 kg/h) จะมีค่า E_c สูงกว่า 98% โดยประสิทธิภาพการเผาไหม้ที่มีค่าสูงเป็นผลมาจาก 1) การติดตั้ง Recirculating ring ซึ่งจะดักจับอนุภาคเชื้อเพลิงขนาดใหญ่ให้หมุนเวียนภายในเบด และ 2) การฉีดอากาศแบบบอร์เทคซึ่งจะดักอนุภาคขนาดใหญ่ที่ติดมากับแก๊สเผาไหม้ให้ตกกลับลงในเบดเพื่อให้ถูกฟลูอิดไคส์อีกครั้ง



รูปที่ 4 การกระจายอุณหภูมิในแนวรัศมีของเตาเผาไหม้ที่ระดับต่างๆ



รูปที่ 5 การเปลี่ยนของปริมาณออกซิเจนภายในเตาเผาไหม้ที่ระดับต่างๆ

ในงานวิจัยนี้ยังมีปรับเปลี่ยนอัตราการป้อนแกลบเพื่อศึกษาสมรรถนะของเตาเผาไหม้ภายใต้การทำงานไม่เต็มพิกัด โดยเริ่มแรกเตาเผาไหม้ที่ถูกออกแบบที่อัตราการป้อนแกลบ 66 kg/h ซึ่งสามารถผลิตความร้อนได้ 250 kW_{th} และมี E_c ที่ 95% หรือสูงกว่านั้น ในการทดลองที่อัตราการป้อนแกลบสูงสุดที่ 73 kg/h ซึ่งคิดเป็นความร้อนที่ผลิตได้ 300 kW_{th} จะมีค่า E_c เท่ากับ 99.4% และที่อัตราการป้อนแกลบต่ำสุดเท่ากับ 33 kg/h (130 kW_{th}) ค่า E_c จะลดลงเหลือ 96.3% ดังตารางที่ 2 โดยจากการทดลองสามารถคิดเป็นค่า Turn-down ratio ของเตาเผาไหม้ได้เท่ากับ 2.3:1

ตารางที่ 2 สรุปผลการทดลองการเผาไหม้เชื้อเพลิงแกลบ

Run	FA	Bed	Exit	Intensity		O ₂ and CO ₂		emissions at 6% O ₁		Unburned carbon in ash	Comb. Eff.
Nos.		Temp. ^a	Temp.	Feed rate	Heat rate	O ₂	CO ₂	CO	NO _x		
	(%)	(°C)	(°C)	(kgm ⁻¹ h ⁻¹)(kg/h)	(MJW/m ²)	(%)	(%)	ppm	ppm	(%)	(%)
Effect of fluidizing air											
1	83	1172	1087	336 (66)	1.40	8.77	11.37	50	232	0.8	99.8
2	119	1153	933	336 (66)	1.39	9.38	11.07	157	295	2.3	99.4
3	132	1106	812	336 (66)	1.39	12.31	8.07	160	318	2.9	99.1
4	164	1056	740	336 (66)	1.37	12.19	8.85	427	336	6.7	98.0
5	174	1049	807	336 (66)	1.34	12.94	6.62	545	352	11.19	95.6
Partial- load operational											
6	117	1136	928	372 (73)	1.54	9.01	11.13	100	288	2.2	99.4
7	140	1120	818	336 (66)	1.38	10.36	9.89	335	300	3.5	98.9
8	220	1006	675	255 (50)	1.03	13.79	5.39	252	337	7.1	97.1
9	380	801	545	168 (33)	0.67	15.74	3.96	2176	348	7.9	96.3

^ameasured at 1.2 m

การใช้ปริมาณอากาศส่วนเกินที่สูงเกินไปจะส่งผลให้อุณหภูมิเบตต่ำลง ซึ่งทำให้ปริมาณแก๊สคาร์บอนมอนอกไซด์ (CO) ที่ท่อทางออกเตาเพิ่มขึ้น จาก 50 เป็น 550 ppm (ที่ออกซิเจนส่วนเกิน 6%) เมื่ออุณหภูมิเบตเปลี่ยนแปลงจาก 1200 เหลือ 1050°C และ CO จะมีค่าเพิ่มขึ้นเป็น 2200 ppm เมื่ออุณหภูมิเบตลดลงถึง 800°C ในกรณีของการลดอัตราป้อนเชื้อเพลิงจาก 77 kg/h เหลือ 33 kg/h ส่วนแก๊สไนโตรเจนออกไซด์ (NO_x) ในทุกเงื่อนไขการทดลองมีค่าในช่วง 230-350 ppm (O₂ ส่วนเกิน 6%) โดยแก๊ส NO_x มีค่าสูงขึ้นเมื่อเพิ่มปริมาณอากาศส่วนเกินจาก 80-170% เนื่องจากไนโตรเจนในเชื้อเพลิงทำปฏิกิริยากับออกซิเจนจากอากาศได้มากขึ้น (Fuel-NO_x)

ในส่วนสุดท้ายเป็นการศึกษาการเผาไหม้แกลบร่วมกับถ่านหินบิทูมินัส โดยใช้แกลบเป็นเชื้อเพลิงหลัก โดยมีสัดส่วนการผสมถ่านหินบิทูมินัสที่ 20 และ 30% (โดยพลังงาน) และใช้ปริมาณ

อากาศส่วนเกินในช่วง 150-220 % ผลการทดลองพบว่า E_c ในกรณีนี้จะมีค่าประมาณ 96% ซึ่งต่ำกว่ากรณีการใช้แกลบเป็นเชื้อเพลิงเพียงอย่างเดียวเนื่องจากถ่านหินเป็นอนุภาคที่มีขนาดใหญ่และมีความหนาแน่นมากกว่าแกลบจึงทำให้เผาไหม้ได้ยาก ส่วนมลพิษที่เกิดขึ้น (O_2 ส่วนเกิน 6%) มีดังนี้คือ CO มีค่าในช่วง 60-160 ppm ส่วน NO_x มีค่าระหว่าง 300-350 ppm

6.4. สรุปผลการทดลอง

- 6.4.1. การเผาไหม้แกลบในเตาเผาไหม้ฟลูอิดไคซ์เบดที่พัฒนาขึ้นนี้สามารถทำได้โดยไม่ต้องผสมวัสดุเชื้อเพลิงในเบดซึ่งลักษณะการเผาไหม้แบบฟลูอิดไคซ์เบดสามารถดูได้จากการกระจายอุณหภูมิที่เป็นลักษณะไอโซเทอร์มอลเบด (Isothermal Bed) รวมถึงการเปลี่ยนแปลงความเข้มข้นของออกซิเจนอย่างรวดเร็วภายในเบด
- 6.4.2. ประสิทธิภาพการเผาไหม้ (E_c) และอัตราการผลิตความร้อน (I_c) ในทุกเงื่อนไขการทดลองมีค่าในช่วง 95.6-99.8% และ $1.34-1.54 \text{ MW}_{th} m^{-2}$ ตามลำดับ ซึ่งเป็นผลของการติดตั้ง Recirculating ring และการฉีดอากาศแบบวอร์เทค
- 6.4.3. การเพิ่มปริมาณอากาศส่วนเกิน โดยการเพิ่มความเร็วอากาศส่วนที่ก่อให้เกิดฟลูอิดไคซ์ชันหรืออัตราการป้อนแกลบ ส่งผลให้ E_c ลดลง เนื่องจากระยะเวลาการเผาไหม้ที่สั้นเกินไปและอุณหภูมิเบดที่ต่ำลง โดยเตาเผาไหม้ตัวนี้เมื่อทำงานไม่เต็มพิกัดจะมีค่า Turn-down Ratio เท่ากับ 2.3:1
- 6.4.4. ปริมาณ CO (คิดที่ 6% O_2) มีค่าเพิ่มขึ้นเมื่อปริมาณอากาศส่วนเกินเพิ่มขึ้นเพราะจะทำให้อุณหภูมิเบดต่ำลง ส่วน NO_x ที่เพิ่มขึ้นเนื่องจากการทำปฏิกิริยาของไนโตรเจนในเชื้อเพลิง (Fuel-N) ที่เกิดขึ้น โดยที่สภาวะการทดลองปกติที่ 66 kg/h จะมีค่า CO และ NO_x (ที่ O_2 ส่วนเกิน 6%) ในช่วง 50-550 ppm และ 230-350 ppm ตามลำดับ
- 6.4.5. เตาเผาไหม้ฟลูอิดไคซ์เบดแบบห้องเผาไหม้สั้นที่พัฒนาขึ้นนั้น สามารถนำไปใช้เผาไหม้แกลบร่วมกับถ่านหินบิทูมินัสได้ ซึ่งการเผาไหม้แกลบและถ่านหินในสัดส่วน 80/20 และ 70/30 (%โดยพลังงาน) โดยมี E_c และ I_c ที่น่าพอใจที่ ในขณะที่แก๊ส NO_x มีค่าเพิ่มขึ้น เนื่องจากสัดส่วนไนโตรเจนในเชื้อเพลิง

6.5 ข้อเสนอแนะ

การวิจัยเกี่ยวกับการเผาไหม้เชื้อเพลิงแกลบหรือชีวมวลชนิดอื่นๆ ร่วมกับถ่านหินควรได้การส่งเสริมและสนับสนุนอย่างจริงจัง โดยเฉพาะเทคนิคการเผาไหม้แบบฟลูอิดไคซ์เบด โดยมุ่งเน้นศึกษาถึงสมรรถนะของการเผาไหม้ร่วม รวมไปถึงปัญหาที่อาจเกิดขึ้นของการเผาไหม้เชื้อเพลิงชีวมวลร่วมกับถ่านหิน เช่น agglomeration sintering และ fouling เป็นต้น

คำหลัก : แกลบ เตาเผาไหม้ ประสิทธิภาพการเผาไหม้ ฟลูอิดไคซ์เบด วอร์เทค

Abstract

f

Project Code: MRG4880011

Project Title: Heat Producing from Biomass Combustion by Fluidized Bed Technique
Integrating with Air Vortexing without Mixing Inert Material into the Bed.

Investigators:

Investigators	Organization
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Project Period: 1 July 2005 – 31 June 2007

Objectives:

1. To promote a use of biomass fuel, as an alternative energy source, in order to substitute for conventional energy sources derived from fossil fuels which are importable and presently highly prized.
2. To develop a combustion technique for a fluidized bed combustor in order to diminish an agglomeration problem and to augment solid-particles circulation within the combustor with a consequence of prolonged resident time of the particles, where height to diameter ratio should be appropriately adopting into the industry.

Methodology:

Fig. 1 shows a schematic diagram of a short-combustion-chamber fluidized-bed combustor (SFBC) with a design output capacity of 250 kW_{th}. The SFBC comprises two main parts (Fig. 2): (1) a cylindrical combustor with 0.5 m i.d., 0.97 m in height, and (2) a conical base with 0.30 m i.d. truncated-apex cone 0.60 m in height designed to contain a bed of ashes and coarse particles. A cylindrical part had a circular ring named a 'recirculating ring' made of refractory with 0.30 m opening diameter located 1.13 m above an air distributor. The recirculating ring divided the combustor into a main (fluidized bed) and minor combustion chambers, and is used to trap entrained particulates in combustion

gases impinging upon its bottom side, as a consequence of solid-gas recirculation inside the fluidized bed.

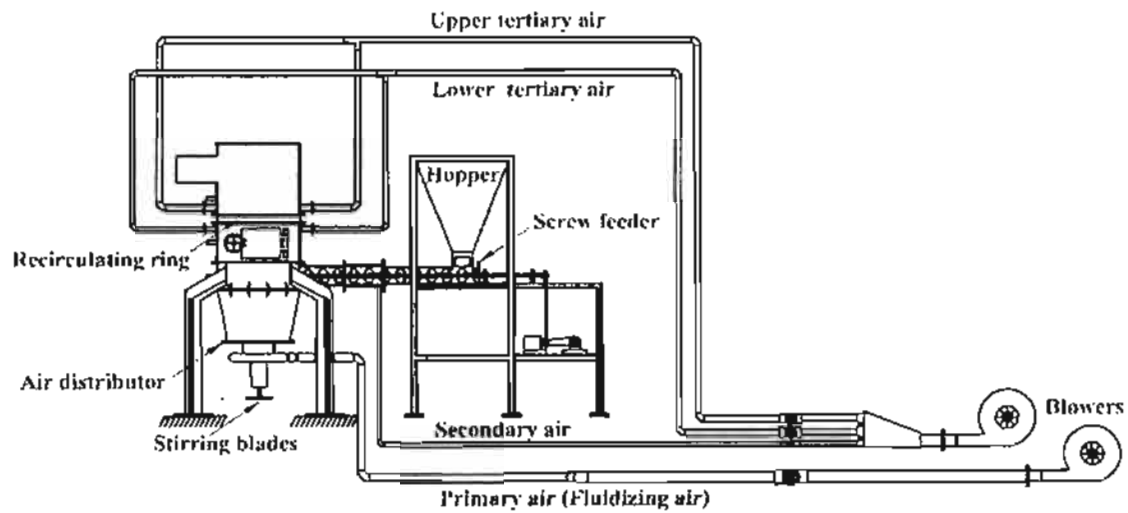


Fig. 1(a) Schematic diagram of short-combustion-chamber FBC, designed output capacity 250 kW_{th}.

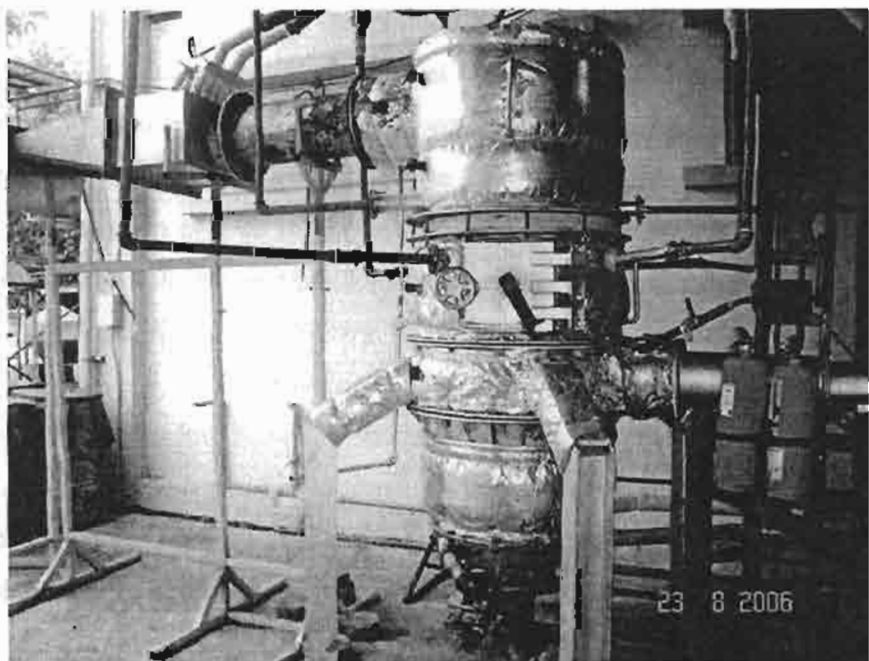


Fig. 1(b) Photograph of short-combustion-chamber FBC, designed output capacity 250 kW_{th}.

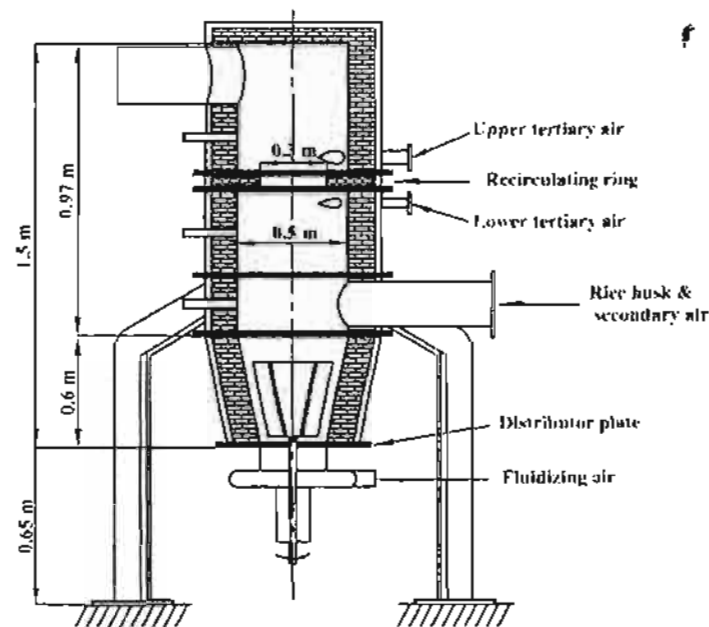


Fig. 2. Axial cross-section of a short-combustion-chamber FBC.

Rice-husk was fed into the FBC via a screw conveyor equipped with a variable-speed drive to regulate the fuel feed rate. The primary air (fluidizing air) was supplied by a 2.2 kW blower. To prevent flame penetrating the fuel feed system, secondary air was injected at the outlet of the screw conveyor. Tertiary air was provided by a 2.2 kW blower and diverted to above and below the recirculating ring. The lower tertiary air was introduced via four air nozzles at an elevation of 1.03 m; the arrangement of these nozzles is shown in Fig. 3a. The air discharging from the nozzles formed a tangent circle of 0.2 m diameter within the confines of the nozzles. Upper tertiary air was introduced tangentially through the two opposing air nozzles (Fig. 3b) positioned just above the recirculating ring. Injecting this air was designed to sweep any particulate materials that may fall on the upper side of the ring towards the fluidized bed below. Moreover, to prevent loose particles formed by rice-husk char agglomeration, air-cooled stainless-steel stirring blades were installed centrally inside the conical base, and operated continuously at 6 rpm.

The desired fuel feed rate was regulated by a variable-speed drive. Air velocity was adjusted manually and measured by hot wire anemometer (accuracy $\pm 3\%$). The

temperature profiles inside the combustor were monitored using a data logger with an accuracy of $\pm 1^\circ\text{C}$ and type-K thermocouples at 0.6, 0.93, 1.33, and 1.58 m above the air distributor. In the same cross-sectional plane of each elevation, the temperatures were also measured radially outward from the combustor center. Gas concentrations were monitored using a multigas analyzer (Testo 350XL). The measuring principle was based on electrochemical cells for O_2 , CO , NO , and NO_2 . A Leco C-H-N-S analyzer was used to analyze unburned carbon content. Combustion and fluidization behaviors during test runs were observed closely via the ports on the combustor's outer surface.

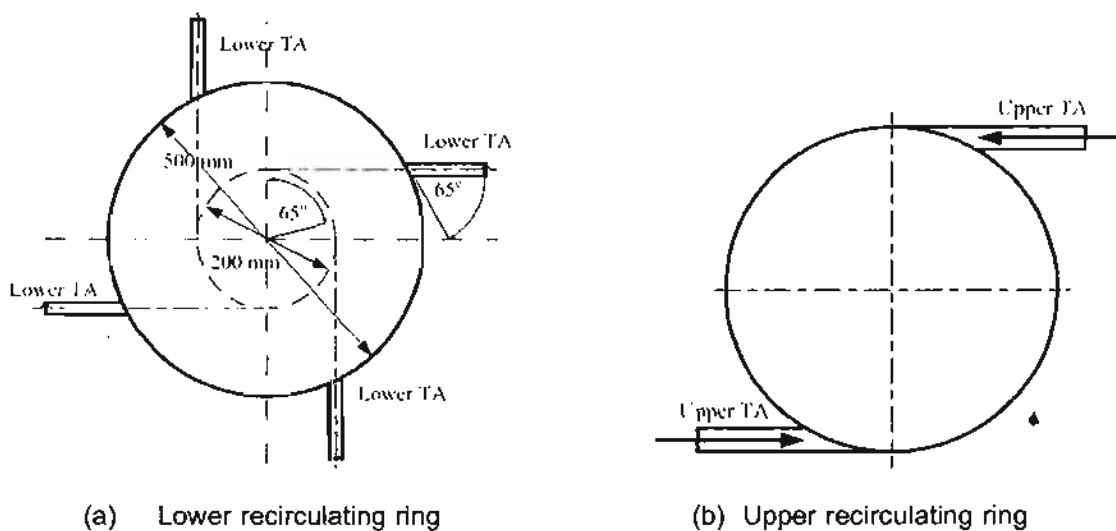


Fig. 3. Arrangement of tangential tertiary air injection

The SFBC can be started easily without any additional fuel, such as liquefied petroleum gas (LPG). Rice-husks were pre-loaded manually into the combustor through an access door until a bed-height of 20-30 cm above the air distributor plate was reached, and then ignited. When rice-husk loaded in advance was continually combusted until the bed temperature reached about 450°C ; thereafter, the feed was increased to the desired feed rate. No external bed material was used to promote fluidized-bed combustion; instead, ash derived from the rice-husk itself during continued combustion, in which the main element is silicon ($\approx 90\%$ as SiO_2), can behave as an inventory bed material that contributes to favorable turbulent gas-solid mixing.

The combustion tests using rice-husk fuel comprised 9 experiments, of which 5 were conducted using varied fluidization velocities and fixed rice-husk feed rates, and another 4 with partial load conditions using fixed total air and varied feed rates. The operating conditions are summarized in Table 1. Three more experiments were performed primarily to investigate the potential for co-firing rice-husk and bituminous-coal in the SFBC.

Table 1
Experimental conditions for rice-husk combustion

Run Nos.	Primary air		Secondary air		Tertiary air				Rice husk feed rate (kg/h)	Excess air (%)	Air-fuel ratio
	Velocity (m/s)	Fraction (-)	Velocity (m/s)	Fraction (-)	Upper recirculating ring		Lower recirculating ring				
					Velocity (m/s)	Fraction (-)	Velocity (m/s)	Fraction (-)			
Effect of primary air											
1	0.5	0.33	16	0.27	8	0.14	15	0.26	66	83	8.32
2	0.8	0.44	16	0.23	8	0.11	15	0.22	66	119	9.96
3	0.9	0.46	16	0.22	8	0.11	15	0.21	66	132	10.56
4	1.2	0.54	16	0.19	8	0.10	15	0.18	66	164	12.01
5	1.4	0.57	16	0.17	8	0.10	15	0.16	66	174	12.47
Partial-load operational											
6	1.0	0.47	15.7	0.22	7.8	0.11	13.6	0.20	73	117	9.87
7	1.0	0.47	15.7	0.22	7.8	0.11	13.6	0.20	66	140	10.92
8	1.0	0.47	15.7	0.22	7.8	0.11	13.6	0.20	50	220	14.56
9	1.0	0.47	15.7	0.22	7.8	0.11	13.6	0.20	33	380	21.84

Results and Discussion:

The temperature profiles showed that combustion mainly took place below the recirculating ring and at between 0.6 m and 0.93 m above distributor plate. Fig. 4 shows typical radial temperature profiles within the combustor. The regions below the recirculating ring were in a near-isothermal bed state, indicating that fluidized-bed combustion characterized combustion in these regions, despite the lack of a secondary solid bed material. This corresponds with visual observations through wall-opening ports and sharp decay of vertical O_2 concentration profile inside the combustor (Fig. 5).

Change in fluidizing velocity or change in fuel feed-rate can result in excess air. All tests under varied conditions allowed excess air of between 83-380%, corresponding to a fluidizing velocity variance of 0.5-1.4 m/s and rice-husk feed rates of 33-73 kg/h. All

experiments shows that bed temperature not $> 1200^{\circ}\text{C}$. Combustion efficiency (E_c) of 95.6-99.8% and heat rate intensity (I_c) in the range $1.34\text{--}1.54 \text{ MW}_{\text{th}}\text{m}^{-2}$ were achieved in the current FBC. The use of high fluidizing velocity (1.4 m/s) caused the distortion of the E_c profile at an excess air of 174%. E_c was quite low (96.7%). However, generally the combustion efficiency was mostly $>98\%$, corresponding to normal operation at feed rates of 66-73 kg/h. The highly effective combustion was presumably due to the efficient recirculation of particulate materials, by utilizing (1) a recirculating ring having a central circular opening, which confined large particles within the fluidized-bed combustion chamber until their sizes diminished, and (2) a vortex generated by the lower tertiary air. This vortex captured large and coarse particulates entrained in the gases by centrifuging them back into the fluidized bed for refluidization.

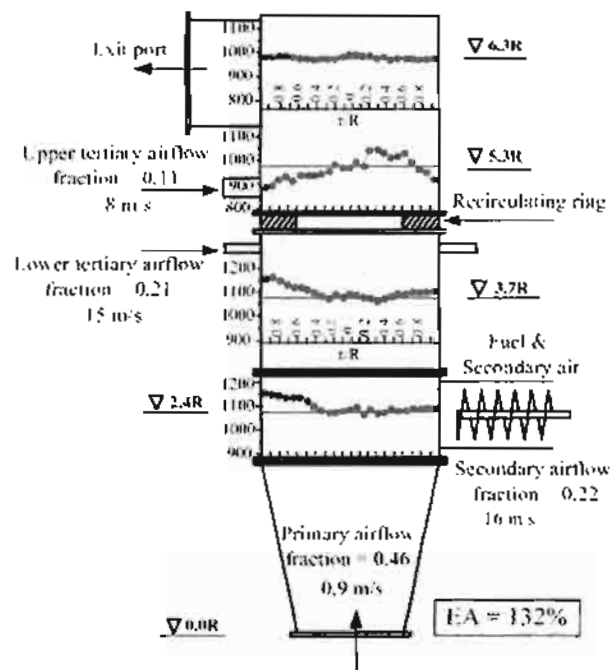


Fig. 4. Typical radial temperature profiles

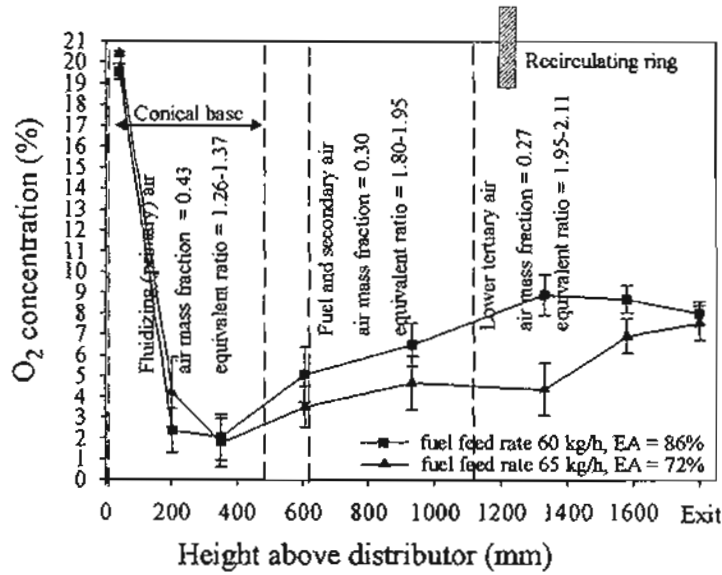


Fig. 5. The O₂ concentration profiles

In this study, various rice-husk loadings were investigated to determine combustor performance under partial-load operation (Table 1). First, the SFBC is designed to burn about 66 kg/h of rice-husk to generate a thermal capacity of about 250 kW_{th} with E_c of about 95% or more. A maximum rice-husk feed-rate of 73 kg/h with thermal capacity of 300 kW_{th} and E_c of 99.4% were achieved. Furthermore, a minimum rice-husk feed-rate of 33 kg/h could yield a thermal capacity of 130 kW_{th} and E_c of 96.3%. Thus, the current combustor has a turn-down ratio (ratio of combustor's maximum output to minimum input) of 2.3:1

Following the CO-concentrations (based on 6% O₂), higher excess air, resulting in lowered bed temperatures, led to the production of higher CO. A moderate increase, from 50 to 550 ppm, can be seen when bed temperature decreased from 1200 to 1050°C. A steep increase to 2200 ppm was detected when bed temperature dropped to 800°C, due to diminishing combustor loading, i.e., from 73 to 33 kg rice-husk/h. In the current work, NO_x emissions were in the range 230-350 ppm (at 6% O₂), depending on combustion conditions. It can be seen in Table 2 that NO_x increased dramatically with increasing excess air, from 80 to 170%. This was due to enlargement of the fuel-NO_x reaction by increased concentration of oxygen.

Table 2

Summary of experimental results for rice-husk firing for operating conditions in Table 1

Run	EA	Bed	Exit	Intensity		O ₂ and CO ₂		emissions at 6% O ₂		Unburned carbon in ash	Comb. Eff.
Nos.		Temp. ^a	Temp.	Feed rate	Heat rate	O ₂	CO ₂	CO	NO _x		
	(%)	(°C)	(°C)	(kgpo ⁻¹ h ⁻¹)/(kgb ⁻¹)	(MWm ⁻²)	(%)	(%)	ppm	ppm	(%)	(%)
Effect of fluidizing air											
1	83	1172	1087	336(66)	1.40	8.77	11.37	50	232	0.8	99.8
2	119	1153	933	336(66)	1.39	9.38	11.07	157	295	2.3	99.4
3	132	1106	812	336(66)	1.39	12.31	8.07	160	318	2.9	99.1
4	164	1056	740	336(66)	1.37	12.19	8.85	427	336	6.7	98.0
5	174	1049	807	336(66)	1.34	12.94	6.62	545	352	11.19	95.6
Partial- load operational											
6	117	1136	928	372(73)	1.54	9.01	11.13	100	288	2.2	99.4
7	140	1120	818	336(66)	1.38	10.36	9.89	335	300	3.5	98.9
8	220	1006	675	255(50)	1.03	13.79	5.39	252	337	7.1	97.1
9	380	801	545	168(33)	0.67	15.74	3.96	2176	348	7.9	96.3

^ameasured at 1.2 m

The final part was devoted to a preliminary study of co-firing rice-husk with bituminous coal, where the primary fuel was rice-husk. Coal and rice-husk were blended on an energy basis, with 2 proportions of coal introduced in co-combustion tests, i.e., 20 and 30% (energy basis). Results obtained for excess air of 150-220% showed that the E_c for fuel blends was about 96%, which was less than for rice-husk alone. The greater difficulty of burning large and dense coal particles responded to the decreased E_c . Moreover, emissions during the co-combustion tests were 60-160 ppm for CO and 300-350 ppm for NO_x.

Conclusion:

1. Without mixing rice-husk with a secondary solid bed material, fluidized bed combustion feature can be accomplished in SFBC developed in this study, indicated by a near-isothermal condition and consumption of abundant oxygen (indicated by axial O₂ concentration profiles), characterized the fluidized-bed combustion feature of this combustor.

2. The combustion efficiency and heat rate intensity of 95.6-99.8% and 1.34-1.54 MWm^{-2} , respectively, were achieved. A combined recirculating ring and vortex air curtain should play an important role in efficient combustion.
3. Increasing excess air, either by increasing fluidizing air velocity or decreasing combustor loading, caused decreases in E_c due to insufficient residence times and bed temperature decreases. The present FBC can operate in partial-load conditions, with an achievable turn-down ratio of 2.3:1.
4. In aspect of gas emissions, increases in excess air resulted in increased CO and NO_x levels. CO increases resulted from temperature drops, whereas NO_x increases were probably due to greater fuel-N reactions with enriched oxygen. Generally, when rice-husk was fired at a normal loading (66 kg/h), CO and NO_x ranges were 50-550 ppm and 230-350 ppm, respectively.
5. The SFBC can be co-fire rice-husk with bituminous coal. Burning rice-husk/coal mixtures of 80/20 and 70/30 (% energy) yielded satisfactory E_c and I_c values. Bituminous blends had higher NO_x emissions attributed to the fuel mixture having a higher nitrogen content.

Recommendation:

The research in a field of co-firing rice-husk/other biomass with coal should be intensively promoted and supported, especially by means of fluidized bed combustion technique and should emphasize on co-combustion performance including such problems may arise—agglomeration, sintering, and fouling, etc.

Keywords: Combustor; Combustion efficiency; Fluidized bed; Rice husk; Vortex.

ชีวมวลเป็นแหล่งพลังงานที่ไม่ก่อให้เกิดการเพิ่มขึ้นของแก๊สคาร์บอนไดออกไซด์ (CO_2 -Neutral) รวมถึงเป็นพลังงานสะอาดและยั่งยืน โดยในช่วงเวลาที่ผ่านมา การเผาไหม้เชื้อเพลิงชีวมวลเพื่อผลิตไอน้ำและไฟฟ้าได้รับความสนใจเพื่อเป็นเชื้อเพลิงทางเลือกทดแทนการเผาไหม้เชื้อเพลิงฟอสซิล ประเทศไทยนั้นวัสดุเหลือใช้ทางการเกษตรที่มีศักยภาพในการนำมาใช้เป็นเชื้อเพลิงคือ แกลบและฟางข้าว โดยแกลบจะเป็นผลพลอยได้จากกระบวนการสีข้าว (20% โดยน้ำหนัก) ซึ่งมีปริมาณประมาณ 4.4 ล้านตัน หรือเทียบเท่าเป็นพลังงานเท่ากับ 6.6×10^7 GJ ทั้งนี้เทคโนโลยีการเผาไหม้แบบฟลูอิดไเบดจะมีความเหมาะสมในการเผาไหม้เชื้อเพลิงแข็งชนิดต่าง ๆ รวมทั้งเชื้อเพลิงแกลบ เนื่องจากมีประสิทธิภาพการแปลงพลังงานและความยืดหยุ่นของการใช้เชื้อเพลิงสูง ในขณะที่การปลดปล่อยมลภาวะค่อนข้างน้อย ทั้งนี้ ปัญหาหนึ่งของการใช้ชีวมวลเป็นเชื้อเพลิงในการเผาไหม้แบบฟลูอิดไเบด คือ การเกิดฟลูอิดเซชันที่ค่อนข้างยาก เนื่องจากรูปทรงที่ไม่เอื้อต่อการฟลูอิดและความหนาแน่นที่ค่อนข้างน้อย จึงมักต้องใส่วัสดุเฉื่อยลงในเบด เช่น ทราบ เพื่อช่วยให้เกิดฟลูอิดเซชัน ซึ่งส่งผลให้มีการใช้พลังงานเพิ่มสูงขึ้น

อย่างไรก็ตาม การใช้แกลบเป็นเชื้อเพลิงเพื่อผลิตความร้อนและไฟฟ้าเพียงอย่างเดียวอาจเกิดปัญหาอันเนื่องมาจากข้าวเป็นผลผลิตซึ่งเกี่ยวได้ตามฤดูกาล และช่วงเวลาของสีข้าวนั้นก็จะมีขึ้นอยู่ปริมาณข้าวที่จะนำมาสีได้ ถ้านหินถูกพิจารณาว่ามีความเหมาะสมที่จะนำมาเผาไหม้ร่วมกับแกลบในช่วงฤดูกาลที่ขาดแคลน เพราะถ่านหินเป็นแหล่งเชื้อเพลิงฟอสซิลซึ่งมีปริมาณที่สามารถนำมาใช้ได้สูงสุดและยังคงเป็นแหล่งพลังงานที่จะมีบทบาทมากในอนาคต

งานวิจัยนี้ได้พัฒนาเตาเผาไหม้ฟลูอิดไเบดแบบห้องเผาไหม้สันขนาดพิกัด 250 kW_{th} โดยไม่ต้องผสมวัสดุเฉื่อยลงในเบดเพื่อทดสอบสมรรถนะในการเผาไหม้แกลบ ได้แก่ ประสิทธิภาพการเผาไหม้ (E_c) อัตราการผลิตความร้อน (I_c) การกระจายอุณหภูมิ และแก๊สมลพิษจากการเผาไหม้ รวมถึงศึกษาผลกระทบของความเร็วอากาศที่ก่อให้เกิดฟลูอิดเซชัน อากาศส่วนเกินและอัตราการป้อนเชื้อเพลิง นอกจากนี้ยังได้ศึกษาการเผาไหม้แกลบร่วมกับถ่านหินบิทูมินัสเบื้องต้นอีกด้วย โดยผลการวิจัยพบว่า เตาเผาไหม้ที่พัฒนาขึ้นนี้สามารถทำงานได้อย่างต่อเนื่องโดยไม่ต้องผสมวัสดุเฉื่อยลงในเบดและมีค่า E_c และ I_c สูง โดยเป็นผลจากการหมุนเวียนของอนุภาคเชื้อเพลิงภายในเบดเผาไหม้เป็นระยะเวลานานซึ่งเกิดจากการติดตั้ง Recirculating ring และการฉีดอากาศแบบเวอร์เทคจึงทำให้ E_c สูงเมื่อเปรียบเทียบกับขนาดห้องเผาไหม้ที่ค่อนข้างสั้น โดย E_c และ I_c สูงสุดที่ทำได้คือ 99.8% และ $1.54 \text{ MW}_{th} \text{ m}^{-2}$ ตามลำดับ ส่วนการเพิ่มความเร็วของอากาศที่ก่อให้เกิดฟลูอิดเซชันและปริมาณอากาศส่วนเกินส่งผลให้ E_c ลดลง สำหรับแก๊สมลพิษ CO และ NO_x พบว่ามีค่าเพิ่มขึ้นเมื่อปริมาณอากาศส่วนเกิน โดยมีค่าในช่วง 50-500 ppm และ 230-350 ppm ตามลำดับ

ส่วนในการศึกษาการเผาไหม้แกลบร่วมกับถ่านหินบิทูมินัส โดยใช้สัดส่วนของแกลบ 70 และ 80% (โดยพลังงาน) ซึ่งผลการวิจัยพบว่า E_c และ I_c อยู่ในเกณฑ์ที่น่าพอใจ ส่วนแก๊ส NO_x มีค่าเพิ่มขึ้น

1. บทความที่คาดว่าจะตีพิมพ์ในวารสารระดับนานาชาติ

1. T. Madhiyanon, P. Sathitruangsak, S. Soponronnarit. Combustion characteristics of rice-husk and preliminary investigation of rice-husk/coal co-combustion performance in a short-combustion-chamber fluidized-bed combustor (SFBC). ส่งตีพิมพ์ในวารสาร FUEL (Impact factor:1.358)

2. บทความประชุมวิชาการในระดับชาติ

1. Madhiyanon, T., Sathitruangsak, P. and Soponronnarit, S., Co-firing between biomass and bituminous coal within a short combustion chamber fluidized bed combustor, Proc. of 20th Conference of mechanical engineering network of Thailand, 2006, 18-20 October 2006, Nakornrachasima, Thailand, paper no. ETM036
2. Madhiyanon, T., Sathitruangsak, P. and Soponronnarit, S., Co-firing between rice husk and bituminous coal within a short combustion chamber fluidized bed combustor , Proc. of 2nd Conference of energy network of Thailand, 2006, 27-29 July 2006, Nakornrachasima, Thailand, paper no. ENETT49-100

Combustion characteristics of rice-husk and preliminary investigation of rice-husk/coal co-combustion performance in a short-combustion-chamber fluidized-bed combustor (SFBC)

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Abstract

A short-combustion-chamber fluidized-bed combustor (SFBC), of 250 kW_{th} capacity, was developed and tested for combustion characteristics of rice-husk, i.e. combustion efficiency (E_c), heat rate intensity (I_c), temperature distribution, and gaseous pollutant emissions. The effects of fluidizing velocity, excess air, and combustor loading were analyzed. The results indicated the system could operate without any secondary solid as bed material, with efficient fuel and combustor utilization, indicated by high E_c and I_c , respectively. Solid recirculation within the bed, created by a solid recirculating ring and an air vortex, played an important role in efficient combustion, even in a relatively short combustion chamber. A maximum E_c of 99.8% and a maximum I_c of 1.54 MW_{th}m⁻² were realized. Increasing fluidizing velocity and excess air caused decreases in E_c . CO and NO_x emissions increased with increased excess air, and were in the range 50-550 ppm and 230-350 ppm, respectively. Finally, preliminary tests of rice-husk co-fired with coal were conducted for 70 and 80% (energy) rice-husk fractions. The results showed satisfactory E_c and I_c , while NO_x appeared to increase.

Keywords: Co-combustion; Coal; Fluidized bed; Rice husk; Vortex

1. Introduction

Biomass is a potential CO₂-neutral, clean and sustainable energy resource. In recent years, burning biofuels to produce steam and power has been of great interest as an alternative to burning fossil fuels. In Thailand, the main agricultural residues with biofuel potential are rice-husk and straw. The annual rice-husk output, a byproduct (20 wt.% of paddy) of the milling process, is about 4.4 million tonnes with an annual energy equivalent of 6.6x10⁷ GJ. Among a variety of combustion technologies, fluidized-bed combustion has proven suitable for burning alternative solid fuels, due to its efficiency in converting fuels to clean energy, fuel flexibility, and clean operation [1-4]. However, many researchers [1, 5-6] experienced difficulties in fluidizing the rice-husk biomass, because of its non-granular, cylindrical shape and low bulk. They strongly suggested that,

to generate satisfactory fluidization, rice-husk must be mixed with an inert bed material, such as sand. The main features of a fluidized-bed combustor (FBC) are high combustion efficiency and grate heat release rate. A combustion efficiency $> 95\%$ has frequently been reported [1, 4, 7-8]. A feed-rate intensity of rice-husk of $395\text{--}510\text{ kg h}^{-1}\text{ m}^{-2}$ was reported in an overview of rice-husk combustion in FBC [1], while $130\text{ kg h}^{-1}\text{ m}^{-2}$ was derived from others [8-9]. Recently, Madhiyanon *et al.* [10] developed a novel combustor named a cyclonic fluidized-bed combustor (ψ -FBC) that integrated swirling and fluidized-bed combustion. A combustion efficiency of 98% was easily obtained and a maximum heat release rate (heat rate per combustor cross-sectional-area) of up to $0.80\text{ MW}_{\text{th}}\text{m}^{-2}$ can be achieved.

The high moisture and alkali content of biomass ash (including forest and agricultural residues, industrial waste, and municipal solid waste (MSW)), makes it difficult to fire alone; therefore, co-combustion with coal is preferable and becoming more attractive, particularly in FBC, for different purposes: power generation [11-13], recovering energy from industrial waste [14-15], and disposal of MSW [16-17]. Apart from reducing CO_2 , biomass co-combustion has been well-proven to reduce emissions of NO_x and SO_x from coal combustion [12-17].

This paper describes the results of an experimental study with a short-combustion-chamber fluidized-bed combustor (SFBC) developed by current authors, thermal capacity $250\text{ kW}_{\text{th}}$, using rice-husk as the primary fuel. This work aimed to clarify combustion characteristics—combustion efficiency, heat rate intensity, temperature distribution, and gaseous pollutant emissions—based on successful approaches to high combustion efficiency and significantly reduced combustion freeboard height [10]. A key design concept for the SFBC was the creation of gas/solid recirculation within the bed, i.e., using a combination of a solid ring acting as a solid barrier and a centrifugal force field acting as an air curtain, and stirring blades to eliminate the problem of loose agglomeration (conglomeration), and consequently not necessitating any inert material mixed into the bed, as stressed in previous studies [1, 5-6]. Although rice-husk is recognized in this study as the primary fuel, since coal is the most abundant fossil-fuel energy source available, it must play an important role as an energy resource for many decades to come. Therefore, the final part of this paper is devoted to investigating the potential results of co-firing rice-husk and coal.

2. Experiment Setup

2.1 The short-combustion-chamber fluidized-bed combustor(SFBC)

Fig. 1 shows a schematic diagram of a short-combustion-chamber fluidized-bed combustor (SFBC) with a design output capacity of $250\text{ kW}_{\text{th}}$. The SFBC comprises two main parts (Fig. 2): (1) a cylindrical combustor with 0.5 m i.d., 0.97 m in height, and (2) a conical base with 0.30 m i.d. truncated-apex cone 0.60 m in height designed to contain a bed of ashes and coarse particles. The combustor was made of steel, the inside of which was lined with fire bricks (0.125 m thk.) and refractory, and the outer surface was insulated with ceramic fiber. A cylindrical part had a circular ring named a 'recirculating ring' made of refractory with 0.30 m opening diameter located 1.13 m above an air distributor. The recirculating ring divided the combustor into a main (fluidized bed) and

minor combustion chambers, and is used to trap entrained particulates in combustion gases impinging upon its bottom side, as a consequence of solid-gas recirculation inside the fluidized bed [10]. The gaseous combustion products coming out the FBC contained the entrained materials--ash, unburned carbon-containing solids--and flew upward into an exhaust pipe at the horizontal center top of the combustor. The exhaust pipe connected to two high-efficiency cyclones in parallel.

Rice-husk was fed into the FBC via a screw conveyor equipped with a variable-speed drive to regulate the fuel feed rate, and a hopper. For co-firing tests, rice-husk was premixed with coal before loading into a hopper. The primary air (fluidizing air) was supplied by a 2.2 kW blower and was injected upward through a wind box mounted on the bottom side of an air distributor (Fig. 2) to generate fluidization. To prevent flame penetrating the fuel feed system, secondary air was injected at the outlet of the screw conveyor. Tertiary air was provided by a 2.2 kW blower and diverted to above and below the recirculating ring, hereafter called upper and lower tertiary air. The lower tertiary air was introduced via four air nozzles arranged in the same horizontal plane, such that they were equally-spaced (90° on the circumferential wall) at an elevation of 1.03 m ($4.12 R$, R = inside radius); the arrangement of these nozzles is shown in Fig. 3a. The air discharging from the nozzles formed a tangent circle of 0.2 m diameter within the confines of the nozzles. The centrifugal force field generated by this vortex was expected to capture the entrained solids ascending with the combustion gases and return them to the fluidized bed [10, 18-19]. Upper tertiary air was introduced tangentially through the two opposing air nozzles (Fig. 3b) positioned just above (1.16 m ($4.64R$)) the recirculating ring. Injecting this air was designed to sweep any particulate materials that may fall on the upper side of the ring towards the fluidized bed below.

To prevent loose particles formed by rice-husk char agglomeration, rather than particles chemically bonding due to ash melt, air-cooled stainless-steel stirring blades were installed centrally inside the conical base, and operated continuously at 6 rpm [10]. Finally, for the co-firing tests, coal was mixed thoroughly with rice-husk to the desired ratio before loading into the feeding system.

2.2 Measurement

The desired fuel feed rate was regulated by a variable-speed drive. Air velocity was adjusted manually and measured by hot wire anemometer (accuracy $\pm 3\%$). The temperature profiles inside the combustor were monitored using a data logger with an accuracy of $\pm 1^\circ\text{C}$ and type-K thermocouples at 0.6, 0.93, 1.33, and 1.58 m above the air distributor. In the same cross-sectional plane, temperatures were measured radially outward from the combustor center, approximately 2 cm apart. The thermocouples were left for a while to allow the temperature to stabilize before recording, and then manually shifted radially to the next position. The flue gas temperature at the exhaust pipe was also measured. Gas concentrations were monitored using a multigas analyzer (Testo 350XL). The measuring principle was based on electrochemical cells for CO , O_2 , NO , and NO_2 . CO_2 is derived from O_2 concentration based on a built-in algorithm in the instrument. A Leco C-H-N-S analyzer was used to analyze unburned carbon content. Combustion and fluidization behaviors during test runs were observed closely via the ports on the combustor's outer surface.

2.3 Experimental procedure

The SFBC can be started easily without any additional fuel, such as liquefied petroleum gas (LPG). Rice-husks were pre-loaded manually into the combustor through an access door until a bed-height of 20-30 cm above the air distributor plate was reached, and then ignited. When pre-loaded rice-husk was being combusted, the access door was closed and simultaneously rice-husks from the feed hopper were gradually conveyed via a screw feeder into the combustor. Combustion continued until the bed temperature reached about 450°C; thereafter, the feed was increased to the desired feed rate. No external bed material was used to promote fluidized-bed combustion; instead, ash derived from the rice-husk itself during continued combustion, in which the main element is silicon ($\approx 90\%$ as SiO_2), can behave as an inventory bed material that contributes to favorable turbulent gas-solid mixing. The duration of each test run was about 6 h, of which 1.5 h was used to achieve steady state. Steady state was determined as steady exit temperature and steady ash rate, measured by collecting and weighing the ash at the cyclone outlet. After steady state was reached, gas concentrations were monitored every 2 min for a 2.5 h-period and averaged over the measurement period. The unburned carbon in the ash collected from the cyclone outlet every 20 min was analyzed and used to determine combustion efficiency. On average, the deviation between the maximum and average unburned carbon content was 14.5%.

2.4 Fuel analysis

Rice-husk and bituminous coal were used as fuel in the experiments. Proximate and ultimate analyses of both fuels are shown in Table 1. Coal particle sizes ranged between 5-10 mm.

3 Results and Discussion

The combustion tests using rice-husk fuel comprised 9 experiments, of which 5 were conducted using varied fluidization velocities and fixed rice-husk feed rates, and another 4 with partial load conditions using fixed total air and varied feed rates. The operating conditions and results of the experiment are summarized in Tables 2 and 3, respectively. Three more experiments were performed primarily to investigate the potential for co-firing rice-husk and bituminous-coal in the SFBC.

3.1. Combustion behavior

The axial temperature profiles within the combustor with varied amounts of excess air are shown in Fig.4; they indicate that maximum temperature occurs at a position below the recirculating ring (~ 0.6 m from the distributor), and decays in the upstream flue gas direction. The temperature profiles showed that combustion mainly took place below the recirculating ring and at between 0.6 m/ 2.4R and 0.93 m/ 3.7R. Decreasing temperatures at locations above the recirculating ring (1.33 m/ 5.3R) were an adverse effect of injecting the upper tertiary air, leading to an unintended mixture with flue gases ascending into the combustor exit.

Fig. 5(a) shows typical radial temperature profiles within the combustor, with general uniformity in the region between 0.60 m/2.4R and 0.93 m/ 5.3 R. The regions below the recirculating ring were in a near-isothermal bed state, indicating that fluidized-bed combustion characterized combustion in these regions, despite the lack of a secondary solid bed material, as previously suggested [1, 5-7]. This corresponds with visual observations through wall-opening ports, i.e., that particulates were fluidized and entrained into the chamber above the conical bed by fluidizing air, apparently corresponding to a uniform flame throughout the entire bed, and the whole bed brightened vigorously. Similar results were experienced in the cyclonic FBC recently developed by Madhiyanon et al. [10]. Two further experiments were performed showing the O₂ concentration profiles inside the combustor, to clarify the characteristics of fluidized-bed combustion commonly maintained in the bed. These profiles are shown in Fig. 5(b). The vertical O₂ concentration profile is characterized by sharp decay at the base of the unit and gradual increase in the upper part due to secondary and tertiary air penetration, indicating the progress of overall combustion. Evidence of the continued consumption of abundant O₂ along the combustor height, from the air distributor up to an elevation where the recirculating ring was placed, indicates vigorous combustion of particulate solids and gases (CO and volatiles) within this region. In addition, the feed-point may represent the first opportunity for burning volatile-rich matter, leading to continued O₂ consumption at that site.

A deeper understanding of the combustion mechanisms of rice-husk can be explained according to thermogravimetrics (TG) and the first derivative of TG (rate of weight-change, DTG) curves, which represent the combustion characteristics of the fuel, as shown in Fig. 6; these results concur with previous reports [20]. It is clear that the devolatilization of rice-husk started at around 180-350°C, volatile and char combustion took place at around 350-500°C, and at around 500°C, no further changes in weight were observed, implying that devolatilization and combustion of biomass with high volatile matter content, such as rice-husk, occurred instantaneously with feeding into the combustor and exposure to high combustor temperatures (>1000°C).

3.2 Combustion efficiency and heat rate intensity

Combustion efficiency (E_c) and heat rate intensity (I_c) for firing rice-husk alone were investigated via two test groups, for which the operating conditions and results are presented in Tables 2 and 3, respectively. E_c is defined by Eq. 1 [10], whereas I_c , viewed as the cross-sectional-area energy utilized can be expressed by Eq. 2.

$$E_c = [(E_f - E_{fg} - E_{ash}) / E_f] \times 100\% \quad (1)$$

where E_f is the heating value of the fuel, E_{ash} is the energy loss as unburned carbon in the ash, and E_{fg} is the energy loss as carbon monoxide in the flue gas.

$$I_c = [\dot{m}_f \times E_f \times (E_c / 100)] / A \quad (2)$$

where \dot{m}_f is the rice-husk mass flow rate and A is the combustor cross-sectional area.

Change in fluidizing velocity or change in fuel feed-rate can result in excess air. All tests under varied conditions allowed excess air of between 83-380%, corresponding to a fluidizing velocity variance of 0.5-1.4 m/s and rice-husk feed rates of 33-73 kg/h. Note that no experiment using less < 80% excess air was conducted because no external load (such as steam) was provided to absorb part of the heat released during combustion,

leading to a limitation of the combustion air, with a consequent bed temperature not $> 1200^{\circ}\text{C}$. As Table 3 shows, E_c of 95.6-99.8% were achieved in the current FBC, comparable with other FBCs (refs. [4, 7] with E_c of 97.0-98.9%, and ref. [8] with E_c of 95.6-96.1%). The present combustor can achieve heat rate intensity in the range $1.34\text{--}1.54 \text{ MW}_{\text{th}}\text{m}^{-2}$, corresponding to normal operation at feed rates of $66\text{--}73 \text{ kg h}^{-1}$, which is comparable with bubbling FBC for rice-husk firing, at $0.65\text{--}2.10 \text{ MW}_{\text{th}}\text{m}^{-2}$ [4, 8-9]; however, it is not competitive with CFBC, at $3.95 \text{ MW}_{\text{th}}\text{m}^{-2}$ [7].

The Changes in E_c and combustion losses with excess air for rice-husk combustion are shown in Fig.7. No bottom ash was drained out during combustion, but all rice-husk ash was elutriated from the combustor exit; this means carbon loss derived from fly ash. Combustion losses are a combination of energy losses due to CO in flue gases and unburned carbon in fly ash. As the figure shows, E_c decreased as excess air increased. The use of high fluidizing velocity (1.4 m/s) caused the distortion of the E_c profile at an excess air of 174%. E_c was quite low (96.7%) when combustion air was introduced at 380% excess air, which led to a relatively low bed temperature of 800°C . Combustion losses due to unburned carbon varied between 0.2-4.2% of energy input, and for CO, 0.02-1.1%.

Mostly, combustion was even within a short distance, i.e., $0.60\text{--}0.93 \text{ m}$ from the air distributor, as previously described (Figs. 4, 5(b)), and $E_c > 98\%$ were generally achievable. The highly effective combustion was presumably due to the efficient recirculation of particulate materials, by utilizing (1) a recirculating ring having a central circular opening, which confined large particles within the fluidized-bed combustion chamber until their sizes diminished [10], and (2) a vortex generated by the lower tertiary air. This vortex captured large and coarse particulates entrained in the gases by centrifuging them back into the fluidized bed for refluidization [10, 18-19].

3.3 Effect of fluidizing velocity and partial load operation

The dependence of E_c on fluidizing air velocity is shown in Fig. 8. A maximum E_c of 99.8% could be accomplished at a fluidizing velocity of 0.6 m/s . When the velocity was increased further, E_c gradually decreased until, with a velocity exceeding 0.9 m/s , values dropped sharply, reaching a minimum of 95.6% at a fluidizing velocity of 1.4 m/s . The consistency of decrease in E_c with increased unburned carbon (wt.%) caught in the cyclones, and decrease in bed temperature, can be seen in Fig. 8. Similar results were also found in the literature [1, 4, 7, 10]. Inefficient combustion with increasing fluidizing velocity can be explained through too-short resident time for complete burning of combustibles, i.e., char particles and gaseous-combustion products.

In this study, various rice-husk loadings were investigated to determine combustor performance under partial-load operation (Table 2). First, the SFBC is designed to burn about 66 kg/h of rice-husk to generate a thermal capacity (defined as fuel energy times E_c) of about $250 \text{ kW}_{\text{th}}$ with E_c of about 95% or more. A maximum rice-husk feed-rate of 73 kg/h with thermal capacity of $300 \text{ kW}_{\text{th}}$ and E_c of 99.4%, however, is possible (Table 3). Furthermore, without any change in combustion air amounts; a relatively lower combustor loading than design can be accomplished with a minimum rice-husk feed-rate of 33 kg/h , yielding a thermal capacity of $130 \text{ kW}_{\text{th}}$ and E_c of 96.3%. Thus, the current combustor has a turn-down ratio (ratio of combustor's maximum output

to minimum input) of 2.3:1, or even higher. As the results, E_c increased as combustor loading increased. This was attributed to bed temperature decrease.

3.4 Flue gas emissions

Fig. 9 shows the dependence of CO and NO_x emissions, as well as bed temperature (at 1.2m), for rice-husk burning on amounts of excess air. A peer review of data included in the figure is shown in Table 3. Following the CO-concentrations (based on 6% O₂), higher excess air, resulting in lowered bed temperatures, led to the production of higher CO. A moderate increase, from 50 to 550 ppm, can be seen when bed temperature decreased from 1200 to 1050°C, indicating the strong influence of bed temperature on CO emissions. This was also observed in a bubbling fluidized bed studied by Armesto *et al.* [4]. A steep increase to 2200 ppm was detected when bed temperature dropped to 800°C, due to diminishing combustor loading, i.e., from 73 to 33 kg rice-husk/h. This is consistent with the observations of Kuprianov *et al.* [8], with high CO emissions in a conical FBC operating under low bed temperatures of around 800°C (2235 ppm at 6% O₂, measured at 2.75 m level and using 100% excess air). With similar combustion conditions, Madhiyanon *et al.* [10] found a trend towards similar CO amounts in rice-husk burning in a novel cyclonic FBC.

For biomass combustion at temperatures <1300°C, NO_x formation is typically through the fuel-NO_x mechanism rather than the thermal formation of NO_x from nitrogen in the combustion air [20-22]. In the current work, NO_x emissions were in the range 230-350 ppm (at 6% O₂), depending on combustion conditions. It can be seen in Fig. 9 that NO_x increased dramatically with increasing excess air, from 80 to 170%, corresponding to 8.8 to 12.9% O₂ measured in the exit flue gas. This was due to enlargement of the fuel-NO_x reaction by increased concentration of oxygen. A consequence of increasing the amount of air, causing significantly increased NO_x, can be noted in ref. [4], where raising excess oxygen from 5 to 10% resulted in a steep increase in NO_x, from 80 to 350 ppm (at 6% O₂). However, providing more combustion air, fuel-NO_x formation will be counteracted by lower bed temperature, with no further increase in NO_x emission (Fig. 9) when excess air >170%. The NO_x emissions of the present FBC (230-350 ppm in 6% O₂ flue gas) were comparable to the bubbling FBCs for firing rice-husk (240-350 ppm in refs. [8-9] and 80-330 ppm in ref. [4]) but higher than a CFB combustor (150-220 ppm in ref. [7]).

3.5 Co-combustion tests

This section is devoted to a preliminary study of co-firing rice-husk with bituminous coal, where the primary fuel was rice-husk. Coal and rice-husk were blended on an energy basis, with 2 proportions of coal introduced in co-combustion tests, i.e., 20 and 30% (energy basis). Results obtained for excess air of 150-220% showed that the E_c for fuel blends was less than for rice-husk alone. The greater difficulty of burning large and dense coal particles, as well as the slower combustion of coal than rice-husk, indicated by the DTG curves in Fig. 6, necessitated longer residence time for coal combustion; these factors together were responsible for lower E_c values. SO₂ emissions were not measured because the gas analyzer did not incorporate a SO₂ chemical cell unit. NO_x emissions followed an increasing trend with percentage coal, particularly for 30% coal share, due to more nitrogen in the fuel with coal added. However, changes in the

amounts of CO were minor, because bituminous coal also contains a high proportion of volatiles (Table 1). Emissions during the co-combustion tests were 60-160 ppm for CO and 300-350 ppm for NO_x.

4. Conclusions

A SFBC of 250 kW_{th} design capacity was developed by adapting techniques from recent work by the present authors, and successfully obtained high combustion efficiency (E_c) and high heat rate intensity (I_c), without the use of a secondary solid to promote fluidization.

A near-isothermal condition, reflected by the radial temperature profiles and consumption of abundant oxygen (indicated by axial O₂ concentration profiles), characterized the fluidized-bed combustion feature of this combustor. Axial temperature and O₂ concentration profiles showed that combustion took place mainly in the lower combustor, below the recirculating ring. Results for E_c and I_c of 95.6-99.8% and 1.3-1.5 MW_{th}m⁻², respectively, were achieved, which were comparable with bubbling FBC for rice-husk firing, however, not competitive with CFBC. A combined recirculating ring and vortex air curtain should play an important role in efficient combustion, even within a confined space.

Increasing excess air, either by increasing fluidizing air velocity or decreasing combustor loading, caused decreases in E_c due to insufficient residence times and bed temperature decreases. The present FBC can operate in partial-load conditions, with an achievable turn-down ratio of 2.3:1. Regarding gas emissions, increases in excess air resulted in increased CO and NO_x levels. CO increases resulted from temperature drops, whereas NO_x increases were probably due to greater fuel-N reactions with enriched oxygen. Generally, when rice-husk was fired at a normal loading (66 kg/h), CO and NO_x ranges were 50-550 ppm and 230-350 ppm, respectively. The final section of this work was a preliminary study of rice-husk co-fired with bituminous coal. Burning rice-husk/coal mixtures of 80/20 and 70/30 (% energy) yielded satisfactory E_c and I_c values. Bituminous blends had higher NO_x emissions attributed to the fuel mixture having a higher nitrogen content.

Acknowledgement

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References

- [1] Natarajan E, Nordin A, Rao AN. Overview of combustion and gasification of rice husk in fluidized bed reactors. *Biomass Bioenergy* 1998;14:533-546.
- [2] Anthony EJ. Fluidized bed combustion of alternative solid fuels: status, success and problems of technology. *Prog Energy Combust Sci* 1995;21:239-268.
- [3] Fabrizio S, Riccardo C. Fluidized bed combustion of alternative solid fuels. *Exp Therm Fluid Sci* 2004;28:691-699.

- [4] Armesto L, Bahillo A, Veijonen K, Cabanillas A, Otero J. Combustion behaviour of rice husk in a bubbling fluidized bed. *Biomass Bioenergy* 2002;23:171-179.
- [5] Rao TR, Bheemarasetti JV Ram. Minimum fluidization velocities of mixtures of biomass and sands. *Energy* 2001;26:633-644.
- [6] Abdullah MZ, Husian Z, Yin Pong SL. Analysis of cold flow fluidization test results for various biomass fuels. *Biomass Bioenergy* 2003;24:487-494.
- [7] Fang M, Yang L, Chen G, Shi Z, Luo Z, Cen K. Experimental study on rice husk combustion in a circulating fluidized bed. *Fuel Process Technol* 2004;85:1273-1282.
- [8] Kuprianov VI, Janvijitsakul K, Permchart W. Co-firing of sugar cane bagasse with rice-husk in a conical fluidized-bed combustor. *Fuel* 2006;85:434-442.
- [9] Permchart W, Kuprianov VI. Emission performance and combustion efficiency of a conical fluidized-bed combustor firing various biomass fuels. *Bioresource Technol* 2004;92:83-91.
- [10] Madhiyanon T, Lapirottanakun A, Sathitruangsak P, Soponronnarit S. A novel cyclonic fluidized-bed combustor (ψ -FBC): Combustion and thermal efficiency, temperature distribution, combustion intensity, and emission of pollutants. *Combust Flame* 2006;146:232-245.
- [11] Spliethoff H, Hein KRG. Effect of co-combustion of biomass on emissions in pulverized fuel furnaces. *Fuel Process Technol* 1998;54:189-205.
- [12] Sami M, Annamalai K, Wooldridge M. Co-firing of coal and biomass fuel blends. *Prog Energy Combust* 2001;27:171-214.
- [13] Laursen K, Grace JR. Some implication of co-combustion of biomass and coal in a fluidized bed boiler. *Fuel Process Technol* 2002;76:77-89.
- [14] Armesto L, Bahillo A, Cabanillas A, Veijonen K, Otero J, Plumed A, Salvador L. Co-combustion of coal and olive oil industry residues in fluidized bed. *Fuel* 2003;82:993-1000.
- [15] Aysel TA, Topal H. Co-combustion of olive cake with lignite coal in a circulating fluidized bed. *Fuel* 2004;83:859-867.
- [16] Dong C, Jin B, Zhong Z, Lan J. Test on co-firing of municipal solid waste and coal in a circulating fluidized bed. *Energy Convers Manage* 2002;43:2189-2199.
- [17] Suksankraison K, Patumsawad S, Vallikul P, Fungtammasan B, Aeearay A. Co-combustion of municipal solid waste and Thai lignite in a fluidized bed. *Energy convers Mange* 2004; 45:947-962.
- [18] Nieh S, Yang G, Zhu AQ, Zhao CS. Measurements of gas-particle flows and elutriation of an 18 inch i.d. cold vortexing fluidized-bed combustion model. *Powder Technol* 1992;69:139-146.
- [19] Lin CH, Teng JT, Chyang CS. Evaluation of the combustion efficiency and emission of pollutants by coal particles in a vortexing fluidized bed. *Combust Flame* 1997;110:163-172.
- [20] Werther J, Saenger M, Hartge EU, Ogada T, Siagi Z. Combustion of agricultural residues. *Prog Energy Combust Sci* 2000;26:1-27.
- [21] Glarborg P, Jensen AD, Johnsson JE. Fuel nitrogen conversion in solid fuel fired systems. *Prog Energy Combust Sci* 2003;29:89-113.
- [22] Zhou H, Jensen AD, Glarborg P, Kavaliuskas A. Formation and reduction of nitric oxide in fixed-bed combustion of straw. *Fuel* 2005;85:705-716.

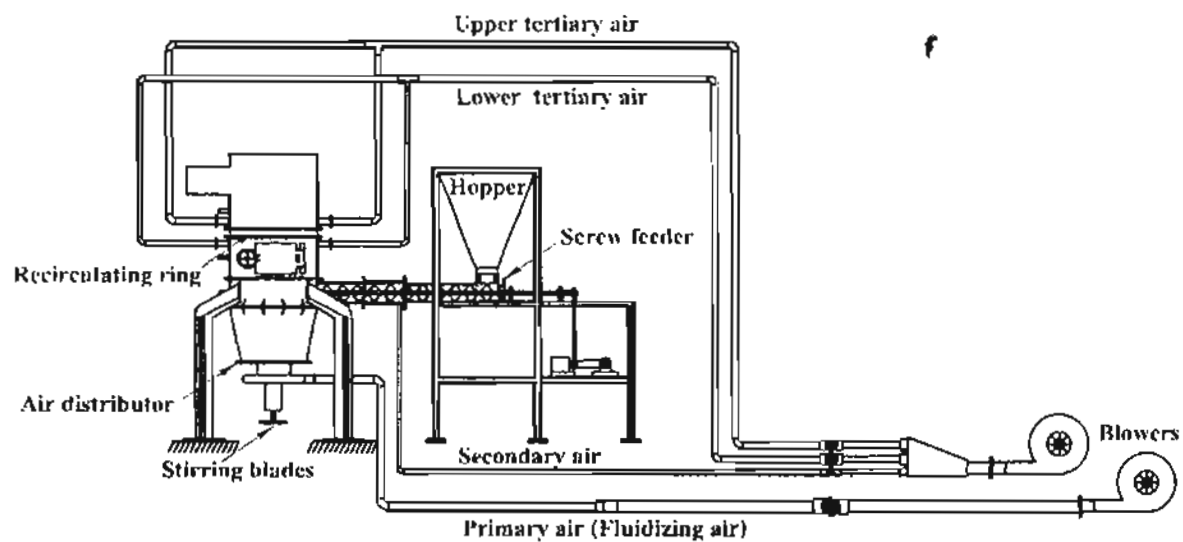


Fig. 1. Schematic diagram of short-combustion-chamber FBC, designed output capacity $250 \text{ kW}_{\text{th}}$.

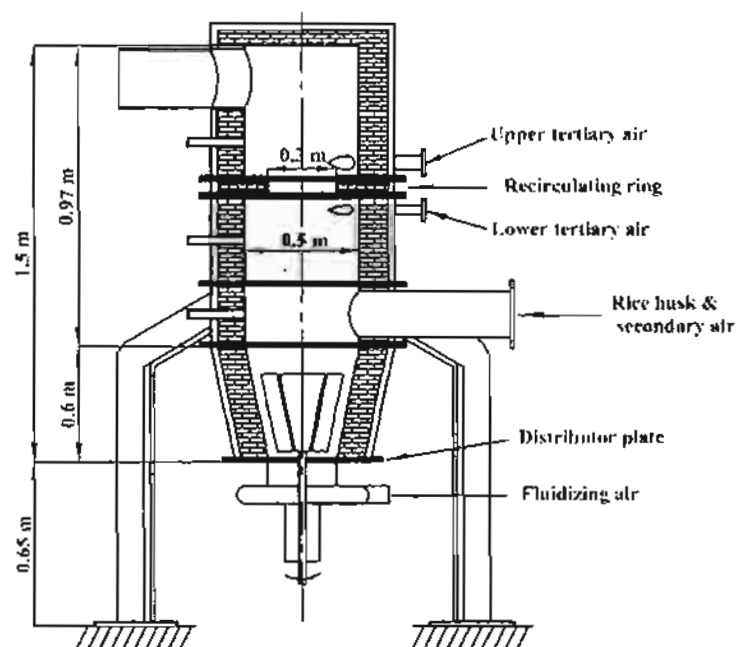


Fig. 2. Axial cross-section of a short-combustion-chamber FBC.

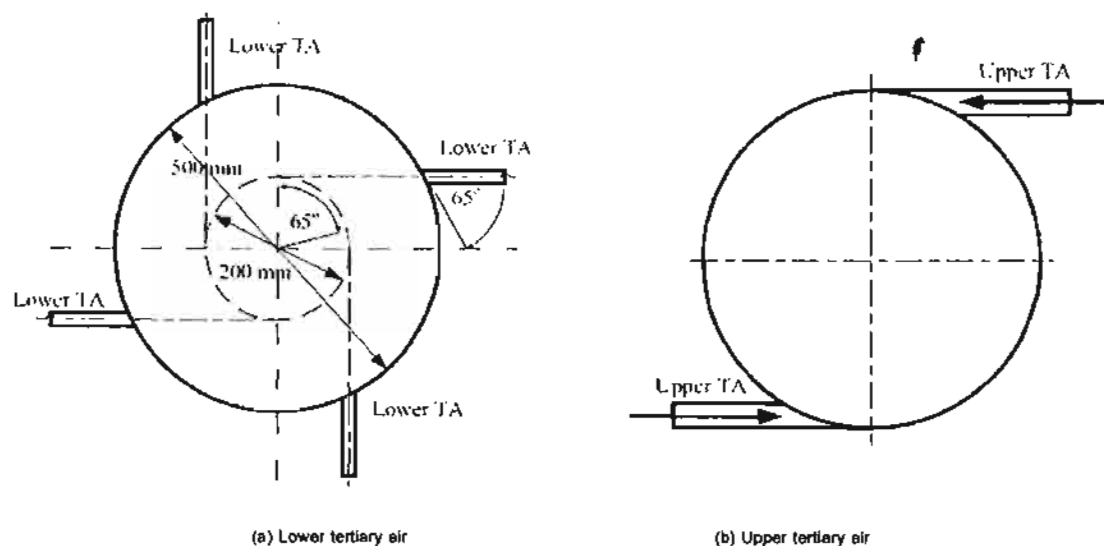


Fig. 3. Arrangement of tangential tertiary air injection, at below the recirculating ring, 1.03 m (a) and at above the recirculating ring, 1.16 m (b).

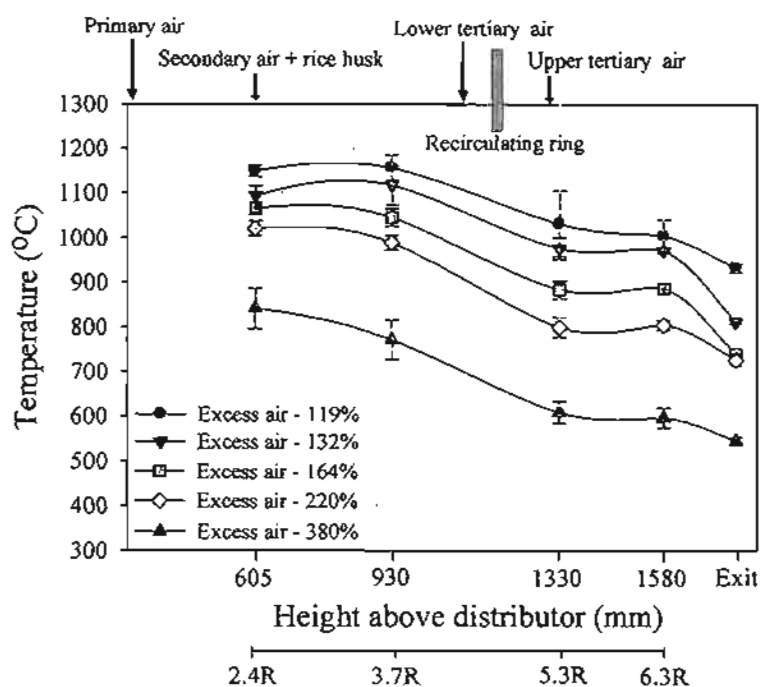


Fig. 4. Axial temperature profiles inside the combustor with different amounts of excess air.

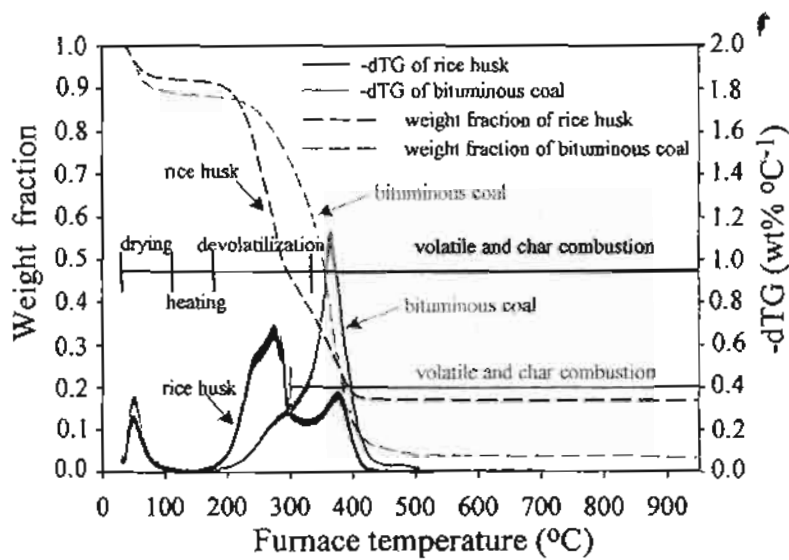


Fig. 6. TG and DTG curves for rice husk and bituminous coal (in air, 5°C min⁻¹).

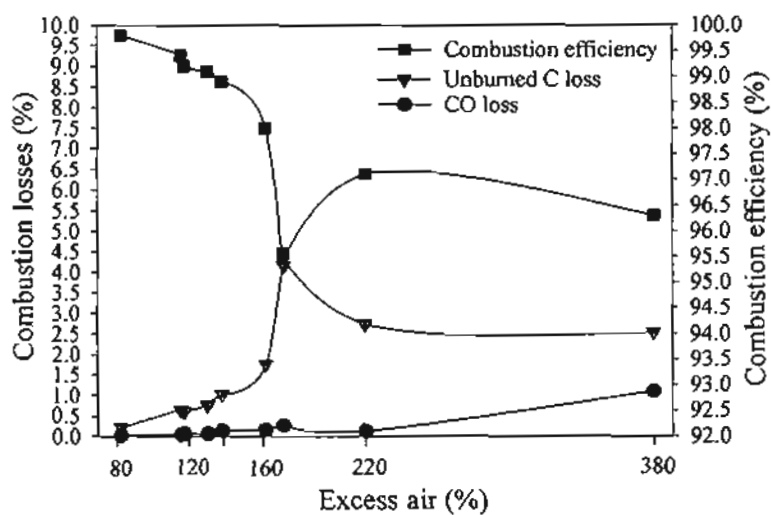


Fig. 7. Change in combustion losses and combustion efficiency with excess air, for rice-husk combustion.

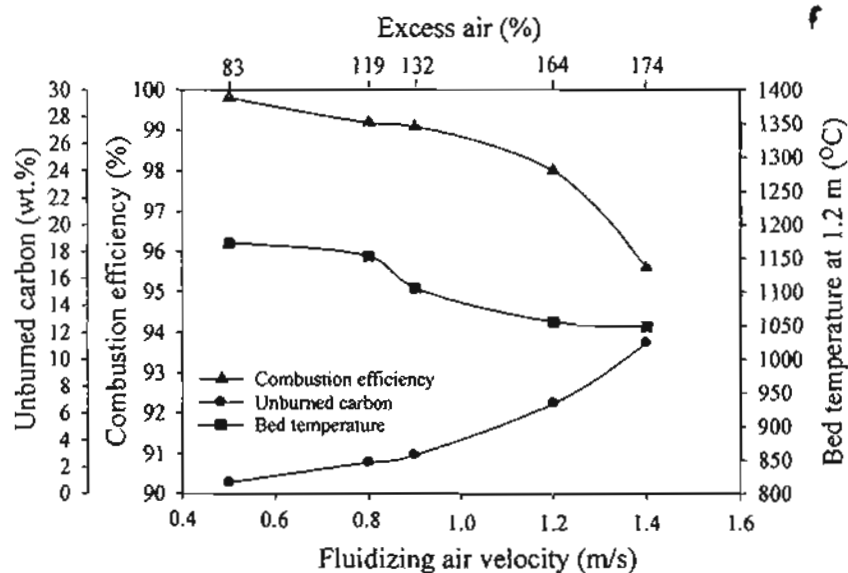


Fig. 8. Effects of fluidizing air velocity and corresponding excess air on combustion efficiency, unburned carbon, and bed temperature.

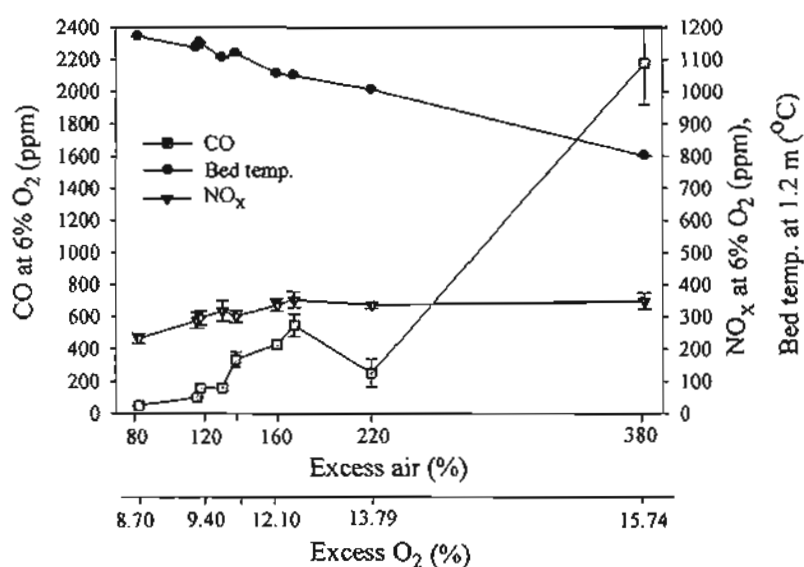


Fig. 9. Changes in CO and NO_x emissions, and bed temperature (at 1.2 m) as a function of excess air.

Table 1
Analyses of rice husk and bituminous coal (as received)

Proximate analysis (wt. %)			Ultimate analysis (wt. %)		
	Rice husk	Bituminous		Rice husk	Bituminous
Fixed carbon	20.1	38.92	C	38.0	57.15
Volatile matter	55.6	32.20	H	4.55	3.29
Moisture	10.3	24.69	O	32.4	14.18
Ash	14.0	4.19	N	0.69	1.20
			S	0.06	1.28
			Moisture	10.3	17.49
			Ash	14.0	5.41
HHV (MJ/kg)					
			Rice husk		Bituminous
			14.98		24.5

Table 2
Experimental conditions for rice-husk combustion

Run Nos.	Primary air		Secondary air		Tertiary air				Rice husk feed rate (kg/h)	Excess air (%)	Air- fuel ratio
	Velocity (m/s)	Fraction (-)	Velocity (m/s)	Fraction (-)	Upper recirculating ring		Lower recirculating ring				
					Velocity (m/s)	Fraction (-)	Velocity (m/s)	Fraction (-)			
Effect of primary air											
1	0.5	0.33	16	0.27	8	0.14	15	0.26	66	83	8.32
2	0.8	0.44	16	0.23	8	0.11	15	0.22	66	119	9.96
3	0.9	0.46	16	0.22	8	0.11	15	0.21	66	132	10.56
4	1.2	0.54	16	0.19	8	0.10	15	0.18	66	164	12.01
5	1.4	0.57	16	0.17	8	0.10	15	0.16	66	174	12.47
Partial-load operational											
6	1.0	0.47	15.7	0.22	7.8	0.11	13.6	0.20	73	117	9.87
7	1.0	0.47	15.7	0.22	7.8	0.11	13.6	0.20	66	140	10.92
8	1.0	0.47	15.7	0.22	7.8	0.11	13.6	0.20	50	220	14.56
9	1.0	0.47	15.7	0.22	7.8	0.11	13.6	0.20	33	380	21.84

Table 3
Summary of experimental results for rice-husk firing for operating conditions in Table 2

Run	EA	Bed	Exit	Intensity		O ₂ and CO ₂		emissions at 6% O ₂		Unburned carbon in ash	Comb. Eff.
Nos.		Temp. ^a	Temp.	Feed rate	Heat rate	O ₂	CO ₂	CO	NO _x		
	(%)	(°C)	(°C)	(kgm ⁻² h ⁻¹)/(kgh ⁻¹)	(MJWm ⁻²)	(%)	(%)	ppm	ppm	(%)	(%)
Effect of fluidizing air											
1	83	1172	1087	336(66)	1.40	8.77	11.37	50	232	0.8	99.8
2	119	1153	933	336(66)	1.39	9.38	11.07	157	295	2.3	99.4
3	132	1106	812	336(66)	1.39	12.31	8.07	160	318	2.9	99.1
4	164	1056	740	336(66)	1.37	12.19	8.85	427	336	6.7	98.0
5	174	1049	807	336(66)	1.34	12.94	6.62	545	352	11.19	95.6
Partial- load operational											
6	117	1136	928	372(73)	1.54	9.01	11.13	100	288	2.2	99.4
7	140	1120	818	336(66)	1.38	10.36	9.89	335	300	3.5	98.9
8	220	1006	675	255(50)	1.03	13.79	5.39	252	337	7.1	97.1
9	380	801	545	168(33)	0.67	15.74	3.96	2176	348	7.9	96.3

^ameasured at 1.2 m

ภาคผนวก

- บทความที่คาดว่าจะตีพิมพ์ในวารสารระดับนานาชาติ
- บทความประชุมวิชาการในระดับชาติ

Manuscript Number: JFUE-D-07-00219R3

Title: Combustion characteristics of rice husk and preliminary investigation of rice-husk/coal co-combustion performance in a short-combustion-chamber fluidized-bed combustor (SFBC)

Article Type: Original Research Paper

Section/Category:

Keywords: Keywords: Co-combustion; Coal; Fluidized bed; Rice husk; Vortex

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Abstract: Abstract

A short-combustion-chamber fluidized-bed combustor (SFBC), of 250 kWth capacity, was developed and tested for combustion characteristics of rice-husk, i.e. combustion efficiency (E_c), heat rate intensity (I_c), temperature distribution, and gaseous pollutant emissions. The effects of fluidizing velocity, excess air, and combustor loading were analyzed. The results indicated the system could operate without any secondary solid as bed material, with efficient fuel and combustor utilization, indicated by high E_c and I_c , respectively. Solid recirculation within the bed, created by a solid recirculating ring and an air vortex, played an important role in efficient combustion, even in a relatively short combustion chamber. A maximum E_c of 99.8% and a maximum I_c of 1.54 MWthm⁻² were realized. Increasing fluidizing velocity and excess air caused decreases in E_c . CO and NO_x emissions increased with increased excess air, and were in the range 50-550 ppm and 230-350 ppm, respectively. Finally, preliminary tests of rice-husk co-fired with coal were conducted for 70

and 80% (energy) rice-husk fractions. The results showed satisfactory E_c and I_c , while NO_x appeared to increase.

Date: 15 August 2007

To: Prof. Akira Tomita,
Principal Editor, *Fuel*

Ref.: JFUE-D-07-00219

Title: Combustion characteristics of rice husk and preliminary investigation of rice-husk/ coal co-combustion performance in a short-combustion-chamber fluidized-bed chamber (SFBC)

Dear Prof. Tomita,

Many thanks for your email of 12 June, regarding the revision of the above paper in JFUE. Overall, the comments were fair, encouraging and constructive. We are convinced that the manuscript has been improved by integration of the recommended revisions. Naturally, we are pleased that Reviewer #2 felt that, in general, the paper is worthy of publication, with some revision. Our responses are briefly listed below. For more detail, please see the attached.

Response to the Editor:

1. With respect to the comment that the manuscript was too long, we have now shortened to 30 pages, partly through condensation and partly through excision. Also included are text, tables, and figures. One part concerning agglomerate formation during co-combustion tests was removed from the revised manuscript, as suggested by Reviewer #1. The manuscript has now been paginated.
2. In response to the comment 'too small letters in figures', we have enlarged them.
3. In the reference section, we have included the titles of the papers.

Response to Reviewer #1:

1. Reviewer #1 thought that the combustor presented in this paper should be classified as a 'cyclone-type combustor' rather than a 'fluidized-bed combustor', as asserted by the authors. We have argued this point further, and explained to Reviewer #1 that the present combustor cannot be classed as a cyclone combustor due to some distinctive features. Fuel was fed into this combustor by a screw-feed system, not by tangential

pneumatic feed, so that no combustion took place along the combustor wall, which is a specific characteristic of solid-fuel cyclonic combustion. Moreover, as stated in the original version, the fluidized-bed combustion phenomenon was reflected by near-isothermal conditions inside the bed (Fig. 5), and together with visual observations via the opening ports in the combustor wall, was also consistent with those quantitative temperature profiles. However, to clarify this issue, as suggested by Reviewer #1 **we performed two further experiments to demonstrate the O_2 profiles inside the combustor at different levels**, the results of which are presented in Fig. 5b of the revised version. The results showed that vigorous combustion occurred just above the air distribution plate, and strengthening of the fluidized bed was characterized in a lower part of the combustor, below the recirculating ring.

2. Reviewer #1 suggested that in order to indicate the fluidized-bed combustor performance, in respect of the available heat rate, a 'grate heat release rate' would be preferred to 'volumetric combustion intensity' (heat rate per unit volume of combustor) used in this study. We thank Reviewer #1 for this comment and concur. In the revised manuscript, volumetric combustion intensity was replaced by heat rate intensity, defined as heat release rate per combustor cross-sectional-area.

3. In the original manuscript, we explained why we conducted some experiments with high levels of excess air. May we clarify further. We intended to investigate combustor performance under partial load. To accomplish this, rice-husk loading was reduced to half, while air velocities were fixed, resulting in an excess air increase of up to 380%. The amounts of combustion air were unchanged because we surmised the combustor would be utilized in rice mills where the thermal load (hot flue gas) requirement may vary due to variations in the supply of rice to be milled. The most convenient method for the operator, when frequently faced with such a situation, is to regulate only the fuel-feed rate. In addition, the heat from the flue gases in this case is useful energy, not waste heat, as the Reviewer noted.

To ensure a fair comparison of the SFBC and other FBCs that use rice-husk as fuel, we compared combustion performance related to heat-rate capacity, combustion efficiency, and emissions separately.

4. With respect to the over-sized manuscript, please see the response to the Editor's comments, item 1.

5. In response to the noted need to improve the English language, we will have the revised version checked and edited again by a native English speaker.

We have responded point-by-point to the specific comments raised by Referee #1, and the responses have been integrated into the revised manuscript (attached).

Response to Reviewer #2

1. We have added more explanation to section 2.3 (Experimental procedure) on how to start-up the SFBC tests and the experimental conditions for the bed material.
- 2, 3. In response to the query why we conducted an experiment with 174% excess air, since this will cause inefficient combustion, we did so because we wanted to investigate the effects of fluidizing air (primary air) velocity on combustion performance in the present combustor. Therefore, the velocity varied from experiment to experiment i.e., starting from 0.5 up to 1.4 m/s, which corresponded to an excess air of 83-174%. However, even operating with 174% excess air and a corresponding velocity of 1.4 m/s, combustion efficiency was still about 95%.
4. Sections 3.2 and 3.3 have been rewritten.
5. With biomass combustion at temperatures $<1300^{\circ}\text{C}$, NO_x formation is typically through the fuel- NO_x mechanism rather than thermal formation of NO_x from nitrogen in the combustion air [Prog in Energ and Combust Sci 26 (2000) 1-27, Prog in Energ and Combust Sci 29 (2003) 89-113, Fuel 85 (2005) 705-716].
6. A/F in Table 2 means air-fuel ratio. This is clarified in Table 2 in the revised version.

Attached is a detailed response to the comments raised by the Reviewers. We sincerely appreciate your consideration of our revised manuscript for publication in *Fuel*, and confirm our willingness to address any further queries.

Yours sincerely,
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Response to comments by Reviewer #1

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At the outset, we sincerely thank Reviewer #1 for offering constructive and encouraging comments, in particular, the excellent and very detailed technical review, which have not only led to better exposition, but also improved the content of our paper. In our paper, we have addressed almost all of the points raised by the Reviewer, and our response to them is presented below.

1. The first suggestion by Reviewer #1 was that the proposed combustor should not be classified as a *fluidized bed combustor* because the inert bed material (typically, sand) was not mixed with fuel to promote fluidization. It was suggested that it is rather a *cyclone-type combustor with a bottom grate*. However, we beg to differ on this point. Simultaneous generation of heat and separation of entrained solids from the flue gases are recognized as important features of a cyclonic combustor. The solid fuel and part of the combustion air are simultaneously injected tangentially to the combustor wall. This generates cyclonic combustion while the solid-gas stream descends along the wall [Combustion and Flame 146 (2006) 232-245; Int. Energy J. 1(2) (2000) 67-75]. Unlike cyclonic combustors, in the present combustor, the fuel was fed directly into the combustor at a location 0.6 m above the air distributor via a screw feeder, not by pneumatic means; the main combustion took place within the chamber below the recirculating ring. The phenomenon of fluidized bed combustion was clearly seen through wall-opening ports, as described in the original manuscript. A near-isothermal bed condition (Fig. 5) also indicated a good mix of the gas-particle stream within the combustor, implying that the features of fluidized-bed combustion prevailed there, even though sand was not used as a bed material. Since the main element of rice-husk ash is silicon (~ 90% as SiO_2), the rice-husk ash that is derived from continued combustion can behave as an inventory bed material that contributes to favorable, turbulent gas-solid mixing.

However, with respect to the reviewer's remark that we *lack information about the O_2 concentration profiles inside the combustor* to clarify this issue, we fully concur. Thus, we have subsequently performed further experiments. The results from two more experiments are presented in Fig. 5b of the revised paper, to illustrate the O_2

concentration profiles at different levels in the combustor (within the conical section at 40, 200, and 350 mm, within the cylindrical part at 605, 930, 1330, and 1580 mm, and at the exit). At the levels associated with the conical section, gases were sampled along the conical wall because the sampling gas probe was unable to extend into the conical base due to the stirring blades inside it. Meanwhile, the O_2 concentration measurements in all regions beyond the conical base were taken along the longitudinal axis of the combustor. The vertical O_2 concentration profile is characterized by sharp decay at the base of the unit and gradual increase in the upper part due to secondary and tertiary air penetrations, indicating the progress of the overall combustion. The evidence for continued consumption of abundant O_2 along the combustor height from the air distributor up to an elevation where the recirculating ring was placed, shows vigorous combustion of particulate solids and gases (CO and volatiles) within this region. Added to this, please note that the feeding-point zone may represent the first opportunity for volatile-rich burning, leading to continued O_2 consumption there. An increase in the O_2 concentrations above the recirculating ring is believed to be attributable to part of the tertiary air (the secondary air in the old version has now changed to tertiary air in the revised version) that is injected below the ring being induced into the upward stream of the combustion gases.

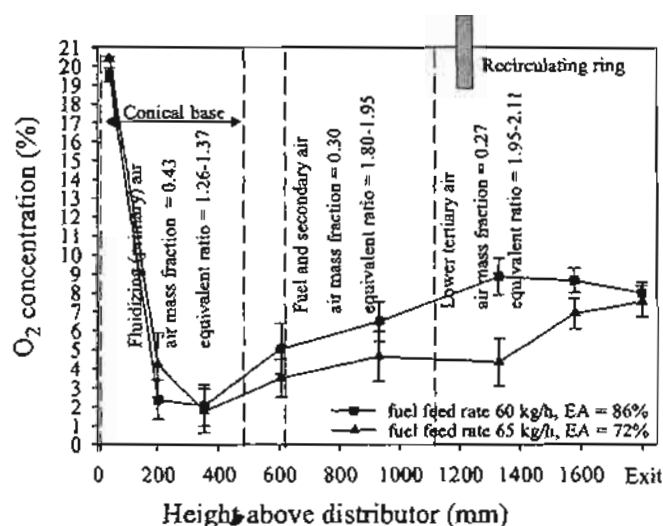


Fig. 5b. The O_2 concentration profiles inside the combustor.

We trust that the above explanation will adequately clarify the combustion process inside the combustor, and has strengthened the argument for the 'fluidized bed combustion' features of this combustor. This is addressed in the revised manuscript.

2. We thank the Reviewer for pointing out that we should use the term 'grate heat release rate' rather than 'volumetric heat release rate' when dealing with combustion performance in FB combustors/boilers, because the height of the combustor depends upon the heat absorption requirements of the combustor walls. We agree on this point and the heat rate intensity, which is defined as the heat release rate per cross-sectional-area of the combustor, has been adopted for the discussion of combustor performance, instead of volumetric combustion intensity. This will be corrected in the manuscript, and the corresponding discussion will be revised accordingly. After recalculation, the present combustor can achieve heat release rates (based on the cross-sectional area of the combustor) in the range $1.34\text{--}1.54\text{ MW}_{\text{th}}\text{m}^{-2}$, corresponding to normal operation at feed rates of $66\text{--}73\text{ kg h}^{-1}$, which can compare with bubbling FBC for rice-husk firing, at $0.65\text{--}2.10\text{ MW}_{\text{th}}\text{m}^{-2}$ [Biomass Bioenerg 23 (2002) 171-179; Bioresource Technol 92 (2004) 83-91; Fuel 85 (2006) 434-442], however, not competitive with CFBC, $3.95\text{ MW}_{\text{th}}\text{m}^{-2}$ [Fuel Proc. Tech. 85 (2004) 1273-1282]. This information will be included in the revised manuscript.

3. The comment by the Reviewer has been rephrased, as follows:

"The authors should explain why they tested the combustors at such high excess-air values, leading to elevated heat losses with exhaust (or waste) gas. For the assumed waste-gas temperature of about $100\text{ }^{\circ}\text{C}$, the heat loss with waste gas is estimated to increase by more than 3% when excess air increases 50% (conventional level) to 150%. Note that the authors tested the combustor at excess air up to 380% (why?), i.e. at quite low thermal efficiency."

We explained in the original manuscript why we performed some experiments with high excess air, but our reasons may not have been clear. We intended to investigate combustor performance under partial load. To accomplish this, rice-husk loading was reduced to half, whereas air velocities were fixed, and this resulted in an excess air increase of up to 380%. The reason for the fixed amount of combustion air with concurrent reduced rice-husk loading was that we foresaw this fluidized-bed

combustor being used in rice mills, as well as small power plants. For rice-mills, the thermal load requirement (for rice drying) may vary, depending on the supply of rice for drying. The thermal energy in the combustion gas leaving the combustor, at about 900°C, can be used to dry rice (paddy) by blending it with induced ambient air, to lower gas temperature to the desired level before drying. The most convenient process for the operator with frequent partial-load situations is to adjust only the fuel-feed rate without disturbing the air flow. In addition, in this case, no heat transfer surface is provided inside the combustor. The hot flue gas leaving the combustor is, therefore, a useful thermal energy resource, not waste energy (gas) and thus no heat loss from flue gas, as the reviewer is aware. Finally, we concur that if the combustor is integrated with a boiler the use of high excess air must not be recommended.

The next point is as follows:

"As stated in the Conclusions, "Results for Ec and Ic of 95.6-99.8% and 0.85-0.88 MWth m-3, respectively, were achieved, which were very competitive with conventional FBCs." Taking into account the above "hidden" heat losses, and, especially, elevated NOx emissions (230-350 ppm in 6% O2 flue gas), it is quite difficult to agree with this conclusion (in terms of the competitiveness with bubbling and circulating FBC systems)."

To avoid misunderstanding of "hidden" flue-gas heat loss, a comparison with FBC will be made based on normal-load conditions only (Run nos. 1-6, Table 3), and the heat-release rate and emissions will be compared separately. The present combustor, however, is competitive with the bubbling FBC for rice-husk burning in some respects, e.g., combustion efficiency (99.4-99.8%) and heat rate intensity (1.34-1.54 MW_m⁻²). The NO_x emissions of the present FBC (230-350 ppm in 6% O₂ flue gas) were comparable to the bubbling FBC for firing rice husk [240-350 ppm, Fuel 85 (2006) 434-442, and Bioresource Technol 92 (2004) 83-91; 80-330 ppm, Biomass Bioenerg 23 (2002) 171-179] but higher than a CFB combustor [150-220 ppm, Fuel Proc. Tech. 85 (2004) 1273- 1282]. The above will be added to the Conclusions of the revised manuscript.

4. With respect to the oversized manuscript, we have now reduced it to 30 pages, partly by condensation and partly by excision. Also included are text, tables and Figs.

In response to the comment *"The authors could be focused towards the rice husk firing only, since the part related to the co-firing of the rice husk with coal is apparently incomplete and weak"*. We agree that the content related to the cause and mechanism of occurrence of agglomerates was not clarified and have thus deleted it, including the corresponding explanation, table and figures. However, the content dealing with co-firing only in respect of combustion performance, as shown in the text, should be of value to all readers, particularly those interested in co-firing biomass with coal, despite it being only a preliminary study. Therefore, only the content dealing with co-combustion performance will be maintained in the revised version.

5. In response to the comment about the need to improve the standard of English, we will have the revised version checked and edited once again by a native English speaker.

Specific comment's Reviewer#1

1. *"use the terms 'primary', 'secondary' and 'tertiary' air in accordance with their conventional meanings (associated with the order of air involvement in the combustion of fuel particles)"*

We agree with the Reviewer. Secondary air and tertiary air have now been adjusted to reflect their order in the combustion cycle.

2. The ground level is shown in Figs. 1 and 2, including the axes of the combustor.

3. After rechecking, it appears that the results for heat loss due to unburned carbon, as presented in Fig. 7, are correct. The use of high fluidizing velocity (1.4 m/s) led to the distortion of the E_c profile at excess air of 174%. This has been fully explained in the original manuscript (section 3.3).

4. Reviewer #1 is correct, the CO and NO_x concentration profiles shown in Fig. 11 should be represented as actual values. However, in order to condense the manuscript we deleted Fig. 11 and corresponding explanation.

Responses to comments by Reviewer #2

At the outset, we sincerely thank Reviewer #2 for his/her work on this paper and the helpful comments provided in this review. They will definitely help to improve the paper and make it clearer. We have addressed almost all of the points raised by Reviewer #2. Our responses are presented below.

1. *"Point 2.3 Experimental procedure: the start of the SFBC tests need more explanation, as well as the experimental conditions relating to bed material."*

The start-up process for the SFBC tests has been explained more clearly, as follows. The SFBC can be started easily without any additional fuel, such as liquefied petroleum gas (LPG). Rice husks were pre-loaded manually into the combustor through an access door until a bed-height of 20-30 cm above the air distributor plate was reached, and then ignited. When pre-loaded rice husk was being combusted, the access door was closed and simultaneously rice husks from the feed hopper were gradually conveyed via a screw feeder into the combustor. Combustion continued until the bed temperature reached about 450°C; thereafter, the feed was increased to the desired feed rate. The above corrections will be added to the revised version.

We apologize for the apparently unclear experimental condition of the bed material. Although it was included in the introduction (final paragraph), results and discussion (section 3.1, 2nd paragraph), and conclusion, it somehow disappeared from the experimental procedure (section 2.3). In fact, no external bed material was used to promote fluidized-bed combustion; instead, ash derived from the rice husk itself during continued combustion, in which the main element is silicon ($\approx 90\%$ as SiO_2), can behave as an inventory bed material that contributes to favorable turbulent gas-solid mixing. We performed two further experiments, as suggested by Reviewer #1, showing the O_2 concentration profiles inside the combustor to clarify the characteristics of fluidized-bed combustion which is commonly maintained in the bed. These profiles will be shown in Fig. 5b in the revised manuscript. The vertical O_2 concentration profile is characterized by sharp decay at the base of the unit and gradual increase in the upper part due to secondary and tertiary air penetration, indicating the progress of overall combustion. Evidence of the continued consumption