47.7% ในกรณีนำถ่านใช้แทนลิกไนต์ สามารถลด CO_2 ได้ 2.5 ล้านตัน หรือถ้านำไปใช้แทนแก๊สธรรมชาติ สามารถลด CO_2 ได้ 1.47 ล้านตัน

ในปี ค.ศ. 1995 ประเทศไทยมีพื้นที่ป่าไม้ประมาณ 82.2 ล้านไร่ [11] แบ่งเป็น ภาคเหนือ 56.2% ภาคตะวันออกเฉียงเหนือ 16.2% ภาคกลางและตะวันตก 12.8% ภาคใต้ 7.48% และภาคตะวันออก 5.32% พื้นที่ป่าชายเลน 1.05 ล้านไร่ จะเห็นได้ว่าประเทศไทยยังมีพื้นที่ในการปลูกป่าเพื่อลด CO_2 ได้ อาจกล่าวได้ว่าถ้าต้องการลด CO_2 ที่ปล่อยจากภาคการผลิตไฟฟ้าทั้งหมด อาจจะมีพื้นที่ป่าไม้ไม่เพียงพอ แต่ถ้าใช้ปี ค.ศ. 1990 หรือ ค.ศ. 1994 เป็นปีฐาน จะทำให้ใช้พื้นที่ปลูกป่าน้อยลง แต่ในอนาคตพื้นที่ป่าไม้ในประเทศอาจลดลง การปลูกป่าเพื่อลด CO_2 จึงทำได้ยาก อาจจะต้องมีการซื้อเทคโนโลยีในการลด CO_2 จากต่างประเทศ แนวทางแก้ไขที่เหมาะสมในการลด CO_2 คือ การจัดการด้านผู้ใช้ไฟฟ้า เปลี่ยนมาใช้เชื้อเพลิงที่มีคุณภาพดีขึ้นหรือสะอาดมากขึ้น ใช้พลังงานทดแทน หรือใช้พลังงานนิวเคลียร์

คำขอบคุณ

ผู้เขียนใคร่ขอแสดงความขอบคุณต่อสำนักงานกองทุนสนับสนุนการวิจัยที่สนับสนุนงานวิจัยนี้

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ตารางที่ 1 การปล่อยแก๊สเรือนกระจกจากภาคกิจกรรมต่าง ๆ ของประเทศไทยในปี ค.ศ. 1990

Unit : Gg (10^3 Gg = 1 million tonne)

Gas/Source	Emission		GWPs	Emission (CO_2 equivalent)	
	Gg	%		Gg	%
Total CO_2 equivalent				225,176.1	100.0
Net Carbondioxide (CO_2)	163,995.7	100.0	1.0	163,995.7	72.8
Fuel Combustion					
Transport	27,634.1	16.9		27,634.1	12.3
Energy Transformation Industries	28,243.4	17.2		28,243.4	12.5
Industry	12,844.8	7.8		12,844.8	5.7
Small Combustion	8,0~~0~~89.0	4.9		8,009.0	3.6
Industrial Process	9,806.7	6.0		9,806.7	4.4
Land Use Change & Forestry					
Changes in Forest and Other Woody Biomass Stocks	19,897.4	12.1		19,897.4	8.8
Forest and Grassland Conversion	81,708.4	49.8		81,708.4	36.3
Abandonment of Managed Lands	-24,148.1	-14.7		-24,148.1	-10.7
Methane (CH_4)	2,746.4	100.0	21.0	57,673.8	25.6
Fuel Combustion					
Transport	7.9	0.3		165.0	0.1
Energy Transformation Industries	0.6	0.0		12.9	0.0
Industry	0.5	0.0		11.0	0.0
Small Combustion	0.8	0.0		17.4	0.0
Fugitive Emission from Fuels					
Oil and Natural Gas	97.4	3.5		2,044.4	0.9
Solid Fuel	10.4	0.4		218.50	0.1
Industrial Process	0.3	0.0		6.6	0.0
Agriculture					
Rice Cultivation	1,786.1	65.0		37,507.2	16.7
Enteric Fermentation	530.1	19.3		11,132.8	4.9
Manure Management	116.0	4.2		2,435.5	1.1
Field Burning of Agricultural Residues	22.1	0.8		463.1	0.2
Land Use Change & Forestry					
Forest and Grassland Conversion	28.2	1.0		591.6	0.3
Waste					
Solid Waste Disposal on Land	121.4	4.4		2,549.6	1.1
Waste water Treatment	24.7	0.9		518.3	0.2
Nitrous Oxide (N_2O)	11.3	100.0	310.0	3,506.6	1.6
Fuel Combustion					
Transport	1.1	9.8		343.6	0.2
Energy Transformation Industries	0.2	1.3		46.8	0.0
Small Combustion	0.2	2.0		69.1	0.0
Agriculture					
Agricultural Soils	9.2	80.9		2,835.7	1.3
Field Burning of Agricultural Residues	0.5	4.3		151.5	0.1
Land Use Change & Forestry					
Forest and Grassland Conversion	0.2	1.7		60.0	0.0

ตารางที่ 2 องค์ประกอบโดยน้ำหนักของเชื้อเพลิงชนิดต่าง ๆ (เปอร์เซ็นต์)

	คาร์บอน	ไฮโดรเจน	ออกซิเจน	ไนโตรเจน	กำมะถัน	เถ้า	ค่าความร้อน (MJ/kg)	kg CO_2/kg fuel
น้ำมันเตา[3]	85.4	10.5	1.5	0.4	2.0	0.1	42.98	3.131
น้ำมันดีเซล[3]	86.5	12.8	0.1	0.1	0.5	-	45.20	3.172
แก๊สธรรมชาติ[3]	64.3	33.2	-	2.5	-	-	45.00	2.357
ลิกไนต์[3]*	31.1	2.2	9.9	1.1	1.4	22.0	12.80	1.140
แอนทราไซต์[17]	86.7	2.2	2.9	0.8	0.5	6.9	33.90	3.179

(3) , (17) ดูได้จากเอกสารอ้างอิง

* ความชื้น 32%

ตารางที่ 3 ปริมาณการใช้เชื้อเพลิง พลังงานไฟฟ้า และการปล่อย CO_2

		Actual[a]		Forecast[b]		
	Unit	1990	1994	2000	2004	2010
Natural gas	GWh	18056.880	30391.310	69829.000	72816.000	66909.000
	M tons	3.232	5.418	11.291	11.753	10.393
	CO_2 (M tons)	7.620	12.770	26.613	27.702	24.496
	$kgCO_2/kWh$	0.422	0.420	0.381	0.380	0.366
Fuel oil	GWh	9067.310	19294.200	3738.000	5421.000	12258.000
	M tons	2.157	4.383	1.006	1.357	2.787
	CO_2 (M tons)	6.754	13.725	3.149	4.249	8.726
	$kgCO_2/kWh$	0.745	0.711	0.842	0.784	0.712
Diesel oil	GWh	259.730	1627.720	25.000	248.000	313.000
	M tons	0.104	0.420	0.014	0.083	0.122
	CO_2 (M tons)	0.330	1.333	0.044	0.263	0.387
	$kgCO_2/kWh$	1.272	0.819	1.760	1.060	1.236
Lignite	GWh	10229.840	14060.630	14387.000	16518.000	16991.000
	M tons	8.889	12.288	13.067	14.979	15.263
	CO_2 (M tons)	10.134	14.008	14.896	17.076	17.400
	$kgCO_2/kWh$	0.991	0.996	1.035	1.033	1.024
Imported coal	GWh	-	-	-	-	13840
	M Tons	-	-	-	-	4.391
	CO_2 (M tons)	-	-	-	-	13.958
	$kgCO_2/kWh$	-	-	-	-	1.008
Hydro	GWh	4858.000	3431.000	3925.000	4556.000	5478.000
Purchased[c]	GWh	691.000	801.000	2863.000	2863.000	17746.000
Total	GWh	43162.760	69605.860	94767.000	102422.000	133535.000
Total	CO_2 (M tons)	24.841	41.836	44.702	49.290	64.967

(a) การไฟฟ้าฝ่ายผลิตแห่งประเทศไทย (Actual)

(b) ฝ่ายข้อมูลพลังงาน สำนักงานคณะกรรมการนโยบายพลังงานแห่งชาติ[7] (Forecast : PDP 97-02)

(c) ซื้อไฟฟ้าจากประเทศลาว

ตารางที่ 4 ปริมาณการรั่วของแก๊สมีเธนจากการขุดเจาะแก๊สธรรมชาติและถ่านหินในประเทศ

Type of Fuel	Unit	Actual				Forecast					
		1990		1994		2000		2004		2010	
		รวม	ผลิตไฟฟ้า	รวม	ผลิตไฟฟ้า	รวม	ผลิตไฟฟ้า	รวม	ผลิตไฟฟ้า	รวม	ผลิตไฟฟ้า
Natural Gas	MMSCF[a]	208415.00	166732.00	378140.00	299300.00	756280.00	596775.00	784020.00	621230.00	450775.00	360620.00
Production	$GgCH_4$	15.09	11.92	27.38	21.67	54.77	43.22	56.78	44.99	32.64	26.12
Venting and Flaring	$GgCH_4$	40.82	32.24	74.05	58.61	148.11	116.87	153.54	121.66	88.28	70.92
Processing	$GgCH_4$	30.61	24.18	55.54	43.96	111.08	87.66	115.16	91.25	66.21	52.97
SubTotal	$GgCH_4$	86.52	68.35	156.98	124.25	313.96	247.75	325.48	257.90	187.13	149.71
Lignite	M tons[a]	12.44	9.81	17.09	12.13	18.61	13.67	21.80	14.98	21.92	15.26
Coal mined	$GgCH_4$	9.59	7.56	13.17	9.35	28.68	21.07	16.80	11.54	16.89	11.76
Total	$GgCH_4$	96.11	75.91	340.29	133.59	328.30	268.81	684.54	269.44	204.03	161.46
GWPs	21										
Total	$GgCO_2$	2018.16	1594.15	3573.10	2805.45	6894.30	5645.01	7187.76	5658.20	4284.47	3390.731

(a) ฝ่ายข้อมูลพลังงาน สำนักงานคณะกรรมการนโยบายพลังงานแห่งชาติ[9]

ตารางที่ 5 พื้นที่ในการลด CO_2 สำหรับไม้แต่ละชนิด

ล้านไร่

ชนิดของป่า	ระยะปลูก (m X m)	ระยะเวลา (ปี)	อัตราเจริญเติบโตเฉลี่ย (tdm / ha / y)	1990	1994	2000	2004	2010
ปริมาณ CO_2 จาก EGAT (M tons)				24.840	41.840	44.700	49.290	64.967
ปริมาณ CO_2 จากการขุดเจาะแก๊สและถ่านหิน (M tons)				1.594	2.805	5.645	5.658	3.390
ผลรวมปริมาณ CO_2 ทั้ง 2 แหล่ง (M tons)				26.434	44.645	50.345	54.948	68.357
ไม้สัก[12]	2 X 2	30	11.56	7.790	13.165	14.845	16.203	20.157
ยูคาลิปตัส[13]	1 X 2	5	17.81	5.059	8.544	9.635	10.516	13.083
สนสามใบ[14]	2 X 2	15	7.70	11.702	19.764	22.287	24.325	30.261
ไม้เลี่ยน[14]	2 X 2	10	11.16	8.074	13.636	15.377	16.783	20.879
โกงกาง[15]	2 X 2	20	13.67	6.592	11.132	12.554	13.702	17.045
กระถินณรงค์[14]	2 X 2	5	6.30	14.303	24.156	27.240	29.731	36.986
กระถินยักษ์[16]	2 X 2	5	7.13	12.637	21.344	24.069	26.270	32.681
สะเดา[5]	2 X 2	20	8.26	10.908	18.424	20.776	22.676	28.209
ประดู่[5]	2 X 2	20	6.80	13.251	22.38	25.237	27.544	34.266

(5),(12),(13),(14),(15),(16) ดูได้จากเอกสารอ้างอิง

ตารางที่ 6 ค่าใช้จ่ายและกำไรสุทธิในการลด CO_2 จากการปลูกป่า

ประเภทปลูกป่า	ชนิดของป่าไม้	รายการ	Unit	1990	1994	2000
อนุรักษ์	ป่าบนบก (ไม้สัก)	ค่าใช้จ่ายรายปี[b]	บาท / ไร่	644.310	644.310	644.310
		พื้นที่ลด CO_2	ล้านไร่	7.790	13.165	14.845
		ค่าใช้จ่ายในการ	Baht / kWh	0.116	0.121	0.100
		ลด CO_2	Baht / t CO_2	189.870	189.990	190.020
	ป่าชายเลน (ไม้โกงกาง)	ค่าใช้จ่ายรายปี[b]	บาท / ไร่	932.670	932.670	932.670
		พื้นที่ลด CO_2	ล้านไร่	6.592	11.132	12.554
		ค่าใช้จ่ายในการ	Baht / kWh	0.142	0.149	0.123
		ลด CO_2	Baht / t CO_2	232.580	232.220	232.570
เศรษฐกิจ	ไม้สัก	ค่าใช้จ่ายรายปี[6]	บาท / ไร่	2438.470	2438.470	2438.470
		พื้นที่ลด CO_2	ล้านไร่	7.790	13.165	14.845
		กำไรสุทธิในการ	Baht / kWh	0.389	0.407	0.337
		ลด CO_2	Baht / t CO_2	635.200	635.700	635.570
		รายได้รายปี[6]	บาท / ไร่	4594.040	4594.040	4594.040
		กำไรสุทธิรายปี	บาท / ไร่	2155.570	2155.570	2155.570
	ยูคาลิปตัส คามาลดูเลนซิส	ค่าใช้จ่ายรายปี[7]	บาท / ไร่	3068.070	3068.070	3068.070
		พื้นที่ลด CO_2	ล้านไร่	5.059	8.544	9.635
		กำไรสุทธิในการ	Baht / kWh	0.010	0.010	0.009
		ลด CO_2	Baht / t CO_2	16.000	16.000	15.990
		รายได้รายปี[7]	บาท / ไร่	3151.710	3151.710	3151.710
		กำไรสุทธิรายปี	บาท / ไร่	83.640	83.640	83.640
	สะเดาเทียม	ค่าใช้จ่ายรายปี[8]	บาท / ไร่	4554.610	4554.610	4554.610
		พื้นที่ลด CO_2	ล้านไร่	10.908	18.424	20.776
		กำไรสุทธิในการ	Baht / kWh	1.302	1.363	1.129
		ลด CO_2	Baht / t CO_2	2125.880	2126.310	2125.970
		รายได้รายปี[8]	บาท / ไร่	9706.590	9706.590	9706.590
		กำไรสุทธิรายปี	บาท / ไร่	5151.980	5151.980	5151.980

(b) ส่วนปลูกป่าภาครัฐ กรมป่าไม้

(6),(7),(8) ดูได้จากเอกสารอ้างอิง

ตารางที่ 7 ค่าใช้จ่ายและกำไรสุทธิในการลด CO_2 จากการปลูกป่าเมื่อใช้ปี 1990 เป็นปีฐาน

ประเภทการปลูกป่า	ชนิดของป่าไม้	รายการ	Unit	1990	1994	2000
ปริมาณ CO_2 จากภาคการผลิตไฟฟ้า			M tons	26.434	44.645	50.345
ปริมาณ CO_2 ที่เพิ่มจากปี 1990			M tons	-	18.210	23.910
อนุรักษ์	ป่าบนบก (ไม้สัก)	พื้นที่ลด CO_2	ล้านไร่	-	5.360	7.050
		ค่าใช้จ่ายในการลด CO_2	Baht / kWh	-	0.049	0.047
			Baht / t CO_2	-	77.350	90.220
	ป่าชายเลน (โกงกาง)	พื้นที่ลด CO_2	ล้านไร่	-	4.540	5.960
		ค่าใช้จ่ายในการลด CO_2	Baht / kWh	-	0.0610	0.059
			Baht / t CO_2	-	94.840	110.410
เศรษฐกิจ	ไม้สัก	พื้นที่ลด CO_2	ล้านไร่	-	5.360	7.050
		กำไรสุทธิในการลด CO_2	Baht / kWh	-	0.165	0.160
			Baht / t CO_2	-	258.790	301.850
	ยูคาลิปตัส	พื้นที่ลด CO_2	ล้านไร่	-	3.480	4.570
		กำไรสุทธิในการลด CO_2	Baht / kWh	-	0.004	0.004
			Baht / t CO_2	-	6.520	7.590
	สะเดาเทียม	พื้นที่ลด CO_2	ล้านไร่	-	7.510	9.560
		กำไรสุทธิในการลด CO_2	Baht / kWh	-	0.556	0.519
			Baht / t CO_2	-	866.640	978.310

ตารางที่ 8 ค่าใช้จ่ายและกำไรสุทธิในการลด CO_2 จากการปลูกป่าเมื่อใช้ปี 1994 เป็นปีฐาน

ประเภทการปลูกป่า	ชนิดของป่าไม้	รายการ	Unit	1994	2000
ปริมาณ CO_2 จากภาคการผลิตไฟฟ้า			M tons	44.645	50.345
ปริมาณ CO_2 ที่เพิ่มจากปี 1994			M tons	-	5.700
อนุรักษ์	ป่าบนบก (ไม้สัก)	พื้นที่ลด CO_2	ล้านไร่	-	1.680
		ค่าใช้จ่ายในการลด CO_2	Baht / kWh	-	0.011
			Baht / t CO_2	-	21.500
	ป่าชายเลน (โกงกาง)	พื้นที่ลด CO_2	ล้านไร่	-	1.420
		ค่าใช้จ่ายในการลด CO_2	Baht / kWh	-	0.014
			Baht / t CO_2	-	26.300
เศรษฐกิจ	ไม้สัก	พื้นที่ลด CO_2	ล้านไร่	-	1.680
		กำไรสุทธิในการลด CO_2	Baht / kWh	-	0.038
			Baht / t CO_2	-	71.930
	ยูคาลิปตัส	พื้นที่ลด CO_2	ล้านไร่	-	1.090
		กำไรสุทธิในการลด CO_2	Baht / kWh	-	0.001
			Baht / t CO_2	-	1.810
	สะเดาเทียม	พื้นที่ลด CO_2	ล้านไร่	-	2.350
		กำไรสุทธิในการลด CO_2	Baht / kWh	-	0.127
			Baht / t CO_2	-	240.480

SOLAR '96

Energy For Life

CONFERENCE PROCEEDINGS

34th Annual Conference

Australian and New Zealand
Solar Energy Society

22 October 1996 - 25 October 1996
Darwin Northern Territory Australia

SESSION 10C: BUILDING PERFORMANCE 3

Chair: Dr A Delsante, CSIRO

1.30pm - 3.10pm SESSION 11: PARALLEL

SESSION 11A: SOLAR THERMAL ENERGY SYSTEMS 3

Chair: Prof S Kaneff, Australian National University

SESSION 11B: POLICY 2

Chair: K Trouchet, International Centre for Application of Solar Energy

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3.30pm - 5.30pm SESSION 12: PLENARY

Chair: Prof W Charters, University of Melbourne

A COMPARATIVE STUDY OF VARIOUS METHODS OF BANANA DRYING

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Abstract

A comparative study of various method of banana drying: natural air flow and used solar energy, natural air flow and used LPG energy and forced air flow and used solar energy with LPG as stand-by auxiliary, was performed at Bang-Kra-Tum, Phitsanulok Province to determine the performance of the dryers operating with each method and analyze the economic probabilities of each dryer. Testing results for the method of natural air flow and used solar energy showed that the average drying time for each batch of banana drying was 6-7 days (57 hours/batch). The total energy consumption was about 19.2 MJ/kg of water evaporated (primary energy) and average of the first law efficiency was about 11.1 %. In the method of natural air flow and used LPG energy, the average drying time for each batch varied between 3, 4 and 5 days (46, 45 and 45 hours/batch respectively). The total energy consumption was about 8.4 MJ/kg of water evaporated (primary energy) and the average of first law efficiency of 3, 4 and 5 day-batch was about 23.6, 28 and 30 % respectively. In the latter method, the average drying time for each batch was 5 days (44 hours/batch). The total energy consumption was about 14.9 MJ/kg of water evaporated (primary energy) and average of the first law efficiency was about 15.8 %.

Concerning economic analysis, it was found that the natural air flow and used solar energy method has a Discount Pay-Back Period (DPBP) of 3.6 years and the benefit per cost ratio (B/C ratio) of 1.2. In the natural air flow and used LPG energy method, the DPBPs and B/C ratios of 3, 4 and 5 day-batch were 0.9, 1.3 and 2 years, and 7.3, 4.9 and 2.9 respectively. The latter method has a DPBP of more than 10 years and B/C ratio of 0.6.

Keywords: Solar dryer/ Dried bananas/ Drying

INTRODUCTION

Drying is one process of food preservation that Thai people have extensively applied to agricultural crop, thus providing added value to the products. Various drying technologies have been recently applied in drying processes to reduce the operational expenses. The use of solar energy is one example although its technologies still require further development for widely uses in drying applications. The region of Phitsanulok and surrounding districts have a considerable amount of "nam-wa" bananas produced, which are commonly dried by open-sun drying, thus exposed to dust, insects, mold and micro-organisms, causing further product quality problems. These problems could be reduced by using an effective solar dryer. Recently, there are 3 drying methods used in

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this area: natural air flow and used solar energy; natural air flow and used LPG energy; and forced air flow and used solar energy with LPG as stand-by auxiliary. The comparison in performance and economics of these methods should be investigated to find the appropriate one.

Wibulswas et al. [1977] determined the drying rate of damp cloth (dipped in water) at 4.2 kg/m^2 -day, by using a solar dryer that permits natural convection of thermal air. Watabutr [1981] determined that the ratio of air distribution ducts relates to the surface area of solar collector, at a rate of 0.11, to deliver an optimum drying efficiency. The slope of the solar collector was 14° and achieved a drying rate of approximately 3.2 kg/m^2 -day. Wibulswas and Thaina [1980] dried damp cloth with a hybrid solar dryer (natural convection) and found that a drying rate was 5 kg/m^2 -day. Excell [1986] developed a solar dryer for paddy using natural convection and achieved a drying time of 2-3 days. Furthermore, some research was conducted to develop a model dryer that employed forced convection of thermal air, generally used for grain drying, as reported by Thongprasert et al. [1985]. Soponronnarit and Tiansuwan [1984$_a$], Soponronnarit and Tiansuwan [1984$_b$], and Boonlong et al. [1984] studied tobacco barn- drying by using solar energy, followed-up by Sitthipong et al. [1987], who modified the drying barn to dry various fruits. Additional information is available in literature written by Soponronnarit [1988] and Soponronnarit [1991]. In addition to these findings, Ong [1986] concluded the research results and developments concerning solar dryer from various Asian countries. Rakwichien et al. [1994] studied a hybrid solar dryer for "nam-wa" bananas that used forced convection by means of an exhaust fan drawing thermal heat from a solar collector via a heat exchanger, prior to entering the drying chamber. The static efficiency of the solar drying system is in accordance with the average moisture content of banana, an optimum efficiency of 30 % and a return on investment between 1.5-5.4 years.

Through the observation of various projects within Thailand, it could be concluded that the use of a solar dryer (natural convection) for bananas is economically feasible (Patranon [1984]), and forced convection is also realized as feasible technology (Soponronnarit et al. [1992] and Sharma et al. [1994]). Therefore the consideration of energy consumption and economic feasibility is important to help selecting the appropriate dryer.

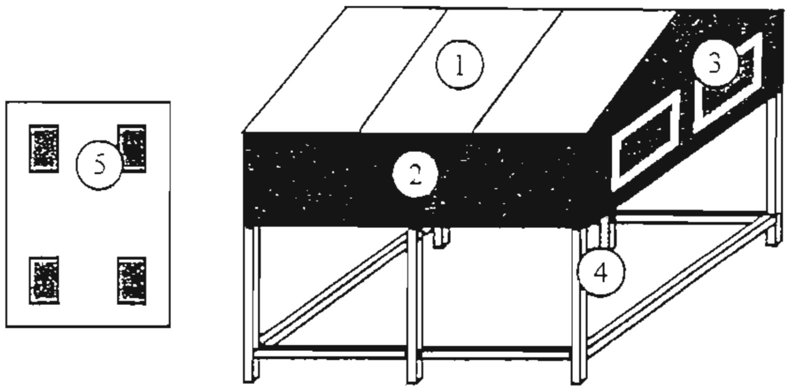
The objective of this research is to compare energy consumption and economics of various types of the banana dryer.

MATERIALS AND METHODS

1. Details of dryers

The details of three banana dryers tested in this research are as follows:
- Natural convection solar dryer

As shown in fig.1, this block-shape dryer, designed by Department of Energy, Ministry of Sciences, Technology and Environments, is made of plywood coated with black color and its cover is made of transparent plastics. Inside the dryer, there is a bamboo tray with area of 0.2×1.5 m^2. Its collector area is 2.64 m^2 and its capacity is 25 kg of fresh banana with 9 kg of dried banana outputs.

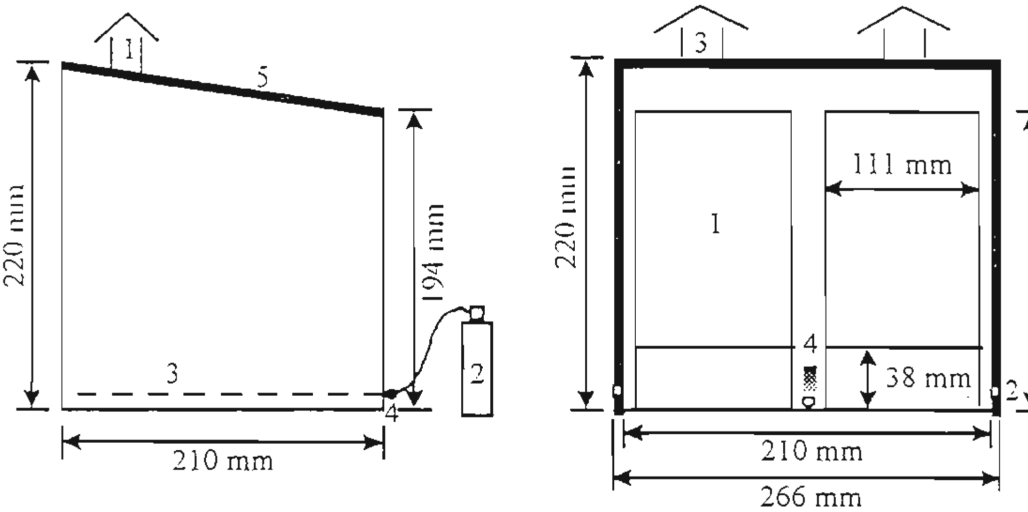


1 = transparent plastic cover, 2 = plywood drying chamber, 3 = air outlet
4 = dryer legs made of wood, 5 = air outlet

figure 1 Natural convection solar dryer

- LPG natural convection dryer

This dryer, as shown in fig.2, designed by Agricultural Machinery Center, Phitsanulok, uses LPG for drying air heating. There are two trolleys with eleven 1.1×1.5 m^2 bamboo trays each in the drying chamber. The side and back walls of the dryer are made of brick coated with cement while the door and roof are insulated by rice husk, 2.4 cm thick, covered with zinc sheet. The dryer capacity is 192 kg of fresh banana with 73 kg of dried banana outputs.



1 = air outlet, 2 = LPG container
3 = burner, 4 = LPG valve
5 = dryer roof

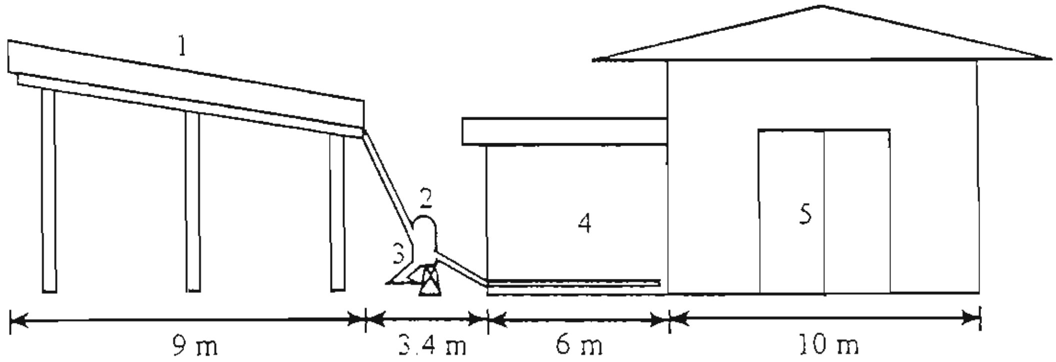
1 = trolleys, 2 = air inlet, 3 = air outlet
4 = the flame from LPG burning

Figure 2 LPG natural convection dryer

- Forced convection solar dryer

This dryer, designed by Asean-Canada Project at Naraesuan University, forces convection of thermal air by using centrifugal fan with 1.5 kW electric motor and has the various solar collector units that separated from the drying chamber (Rakwichian[1994]) (see fig.3). The heat transfers from the collectors to the air in flow-channel which is later exits at collector outlet. In case of insufficient temperatures, LPG will be a stand-by auxiliary that directly heats ambient air in a junction burner located near the exhaust fan. One drying system comprises of 23.1 m^2 of solar collector area and a drying chamber of

1 73m × 2m × 6m long that accommodates three trolleys, five shelves and sixty trays In operation, the air passes through the solar collector and directly enters the drying chamber through four perforated ducts located on the chamber floor. After that it further moves vertically past the drying bananas before exits at the chamber roof through six outlets.



1 = collector, 2 = Blower, 3 = burner stove
4 = cabinet dryer, 5 = Facilitating room

Figure 3 Forced convection solar dryer

2. Experiments

The experiments for each type of dryer are as follows:

- Natural convection solar dryer

Spread 25 kg of peeled ripe bananas on the dryer tray and dry them during daytime. At the end of the first and second day of drying, collect all bananas, put them in plastic bag and keep them all night to start on sweetening before spread them on the tray again on the day after. During night time of the third, fourth and fifth day of drying, pile all bananas in the middle of the tray to prevent case hardening. After the fifth day of drying, all bananas are flattened and further dried for another two days to complete the process. Seven dryers are used in this experiment to obtain continuous output of dried banana every day.

- LPG Natural convection dryer

This experiment is composed of circle drying process(4 and 5 days) and continuous drying process (3 days). In the circle process of 5 day drying, 192 kg of ripe bananas are dried during daytime every day. At the end of the first, third and fourth day of drying, all bananas are piled in the middle of the tray and left all night to prevent case hardening while at the end of the second day they are collected and kept in plastic bag all night to start on sweetening. In the middle of the fourth day, the bananas are flattened before being further dried on the last day, completing the process. Starting from the second day of the 5 day drying process is the process of the 4 day drying. The drying temperature of both drying processes is approximately 50 °C. In the continuous process, 192 kg of peeled ripe bananas are dried with drying temperature of 60 °C for 9 hours on the first day of drying before being collected and kept in plastic bags all night. After that, being flattened in the middle of the second day, they are further dried for 2 days to complete the process.

- Forced convection solar dryer

The experiment was conducted with 360 kg of peeled ripe bananas. The experimental process is the same as the 5 day circle process of LPG Natural convection dryer.

The three experiments mentioned above collected the following data:

- Air flow rates were determined by the average air-flow velocity of the exhaust air at the cross-section of the air product, with a fan anemometer.
- Temperature, entering and exiting solar collector, was measured by a type K thermo-couple connected with data logger with the accuracy of ±1 °C and recorded at one hour intervals.
- Total solar radiation received on the solar collector surface, was measured by a solar indicator with the accuracy of ± 5%.
- LPG consumption was determined by recording LPG weight displaced.
- Electrical consumption of the centrifugal fan was measured with a camp and meter (Yokogawa), with the accuracy of ± 1%
- Moisture content of the product, by the random selection of two banana samples, was weighed by accurate scales, then cut into small pieces and dried in an oven at 103 °C for 72 hours.
- Water evaporation was measured by large scales (Max.cap. 60 kg), with the accuracy of ± 0.1 kg, and recording weight changes before and after each drying period.

RESULTS AND DISCUSSION

- Results of banana drying testing

The results of banana drying testing of various methods are depicted in Table 1.

Table 1 The results of banana drying testing of various methods

	NCSD[A]	LPGD[B]	FCSD+LPG[C]
Initial weight of bananas (kg)	25	192	360
Final weight of bananas (kg)	9	73	141.1
Water evaporation loss (kg)	16	119	218.9
Total solar radiation at collector surface (MJ)	292.3	-	1,814.9
Total energy consumption of LPG (MJ)	-	971.2	1,060.4
Total electrical consumption of fan (MJ)	-	-	393.8
Total energy consumption (MJ)	292.3	971.2	3,269.2
Latent heat of evaporation (MJ/kg)	2.4	2.4	2.4
First law efficiency (%)	13.1	29.4	16.1
Average first law efficiency (%)[D]	11.1	23.6|28.5|30[E]	15.8
Specific energy consumption (MJ/kg of water evaporated)	18.3	8.2	14.9

Remark: NCSD = Natural Convection Solar Dryer
LPGD = LPG natural convection Dryer
FCSD + LPG = Forced Convection Solar Dryer with LPG as auxiliary
A = test results between 11-16 APR 1995.
B = test results between 13-16 DEC 1995.
C = test results between 15-19 MAY 1995.

D = Average first law efficiency of all experiments.

E = Average first law efficiency of 3, 4 and 5 day drying respectively

LPG Low Heating Value = 46.693 kJ/kg

From all tests, it was determined that initial moisture content of the fresh banana was between 230-300 % dry basis, and average final moisture content upon natural solar drying, LPG drying, and Solar and LPG drying of 50, 47 and 47.3 % dry basis respectively. As reported on the table, the specific energy consumption of the LPG drying process is lower than that of both solar drying processes. This may be caused by the higher temperature in the drying chamber of the LPG dryer which brings the higher drying rate.

- Physical property of dried bananas

The color of dried banana skin from natural convection solar dryer, measured by R.H.S. Colour Chart, was Greyed-Yellow 162 group B while those from the LPG and forced solar drying process were darker, Greyed-Orange 163 group A. This is caused by higher temperature in drying chamber which leads to nonenzymatic browning reaction such as caramelization.

- Economic analysis

Details of economic analysis are shown in table 2.

Table 2 Details of Economic Analysis (per year)

	NCSD	LPGD			FCSD−LPG
		3 days	4 days	5 days	
Project life	5	10			10
Fixed cost					
- Land rent (increase 20% every 5 years)	250	250			1,000
- Number of dryers	7	5			1
- Dryer cost	28,000	125,000			1,350,000
Variable cost					
- Labour cost (increase 10% every year)	18,000	84,000			84,000
- operating cost	4,836	43,396	32,376	25,916	75,430
- Banana cost (increase 0.5 baht/kg every 2years)	27,900	328,896	245,736	196,416	571,680
- LPG cost (12 baht/kg, increase 10% every year)	-	171,300	112,300	87,978	101,085.30
- Electricity cost (2.5 baht/unit)	-	-			42,262.20
- Maintenance cost (baht/year)	515	500			6,000
- Others (baht/year)	500	500			20,000
Incomes					
- Amount of dried bananas per year	3,348	41,683	31,098	24,893	56,012
- Dried banana cost (19 baht/kg, increase 10% every 2 years)	63,612	791,977	590,862	472,967	1,064,228

Remark: 1 US$ = 25 Baht

According to the details in the above table and using method of Discounted Pay Back Period (DPBP)with 12% discount rate. it was determined that DPBP of natural convection solar dryer. LPG dryer (3, 4 and 5 day), and forced convection solar dryer were 3.6, 0.9. 1.3, 2 and more than 10 years respectively. The net benefit of natural convection solar dryer. LPG dryer (3, 4 and 5 day), and forced convection solar dryer were 12000, 143135, 115396, 97404 and 163535 baht per year respectively. For benefit per cost ratio (B/C ratio) with interest rate of 12 %, it was found that B/C ratio of natural convection solar dryer, LPG dryer (3, 4 and 5 day), and forced convection solar dryer were 1.2, 7.3, 4.9, 2.9 and 0.6 respectively. The DPBP of the forced convection solar dryer was dramatically higher and B/C ratio was significantly lower. These were because of high investments.

CONCLUSION

1. The average efficiency of LPG dryer is higher than those of solar dryers: 23.6%, 28.5% and 30% of 3, 4 and 5 day drying respectively compared with 11.1% in natural convection solar dryer and 16% in the forced convection solar dryer.
2. The dried banana skin color of LPG and forced convection solar dryer are darker than that of natural convection solar dryer.
3. The best condition of banana drying investment is the 3-day drying with LPG.

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POTENTIAL OF RICE MILL'S COGENERATION IN THAILAND

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Abstract

Electricity and thermal energy used in white rice mill are approximately 190 MJ/ton paddy (53kWh/ton paddy) and 242 MJ/ton paddy respectively, while in par-boiled rice mill, electricity and thermal energy used are approximately 238 MJ/ton paddy (66 kWh/ton paddy) and 1,019 MJ/ton paddy respectively. If the rice mill's cogeneration system using a 160 kWh gasifier with internal combustion engine connected with power generator is employed to maximize electricity generating, it may render some excessive energy. Total electricity generated by 260 white rice mills is 112 MW, of which 87% is used in the rice mill and 13% is excessive. Heat generated can dry 50% of the total paddy to be milled. For 52 par-boiled rice mills, total electricity generated is 32 MW, of which 88% is used in the mill and 12% is excessive. Heat from gasifier with internal combustion engine is not enough for heating process. Thus a boiler is needed to be added in order to generate heat for using in soaking and par-boiling processes. The heat obtained can dry 80% of the total paddy to be milled. In using steam turbine system in the rice mill's cogeneration, total electricity generated by 260 white rice mills is 150 MW, of which 60% is used in the mill and 40% is excessive. Heat of flue gas from boiler can dry the total of paddy to be milled. Total electricity generated by 52 par-boiled rice mills is 29 MW, of which 97% is used in the mill and 3% is excessive. Heat of flue gas from boiler, high-pressure steam and condensate from condenser is employed to be used in soaking and par-boiling processes. The heat obtained can dry 78% of the total paddy to be milled.

The government encourages private sectors to generate electricity by using biomass fuel and sell back to the Electricity Generating Authority of Thailand (EGAT). Biomass fuel, when combusted, produces CO_2 that can be reused (tree uses in photosynthesis process) and does not cause accumulative CO_2 in atmosphere. The average cost in reducing CO_2 by forestation is approximately 0.38 baht/kWh. This process increases the electricity generating cost. Furthermore, the average cost in eliminating SO_2 is 0.15 baht/kWh. Therefore, EGAT should raise additional price of 0.38 baht/kWh or 0.53 baht/kWh to purchase the electrity generated by using biomass fuel from private sector.

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INTRODUCTION

In 1994 in Thailand, there were 312 rice mills of which 52 were par-boiled rice mills and 260 were white rice mills, each with a production capacity over 100 tons/day. These rice mills were taken into consideration for the potential of electricity generation within the mill using husk fuel. The amount of husk in rice mill with a capacity lower 100 tons/day was not enough to be used as fuel. Generally, two types of energy used in rice mills were electrical energy and thermal energy. In some rice mills only electrical energy was used whereas in other rice mills energy from electricity and steam engine were used in milling process. For par-boiled rice mills, electrical energy and steam from steam boiler were used. Thermal energy from steam was used in the processes of par-boiling, paddy drying and soaking. In drying process, thermal energy from flue gas from steam boiler might be used. Some rice mills used energy from steam to drive steam engine connected with a shaft of milling machine. As rice mills used both electrical and thermal energy, there was the potential of cogeneration system for rice mills.

Cogeneration has been a technology developed and used for a long time by the industries in America, Europe and Asia. It is a cogeneration of thermal energy and power. Electrical (mechanical energy) and thermal energy are generated continously from the same fuel source. Cogeneration makes the energy using more effective, highest benefits but lowest energy consumption. Cogeneration is divided into two types, according to the types of energy produced and the order of energy using. They are Topping cycle and Bottoming cycle. Topping cycle is a system that produces electricity or mechanical energy by using fuel and then convey the heat obtained to be used further. Bottoming cycle is a system which uses energy from fuel to produce thermal energy to be used in production process. The heat from the production process is then released out to generate mechanical power or electrical power.

The objectives of this paper are to analyze the electrical and thermal energy consumption in white rice mills and par-boiled rice mills, and to present the application of cogeneration system for rice mills as well as the appropriate electricity price to be bought back by electricity producers.

OPERATION OF RICE MILLS

Currently, in-country rice mill with a capacity of 100 tons/day has two types of milling; white rice milling and par-boiled milling.

White rice milling

Principal equipment composed in white rice milling are paddy husker, husk separator, rotary sifter for separating brown rice and paddy, whitening machine, bran separator, polishing machine, rice cleaner and rice grader. Milling process is shown in Figure 1.

Par-boiled rice milling

The milling process in par-boiled rice milling is the same as white rice milling but par-boiling process is to be added. Paddy is recommendable to be par-boiled before milling in order to gain more head yield. In addition, in par-boiling, vitamin and mineral can absorb into the grain and produce more nutrition as compared with white rice at the same level of whitening. Details of milling process is shown in Figure 2.

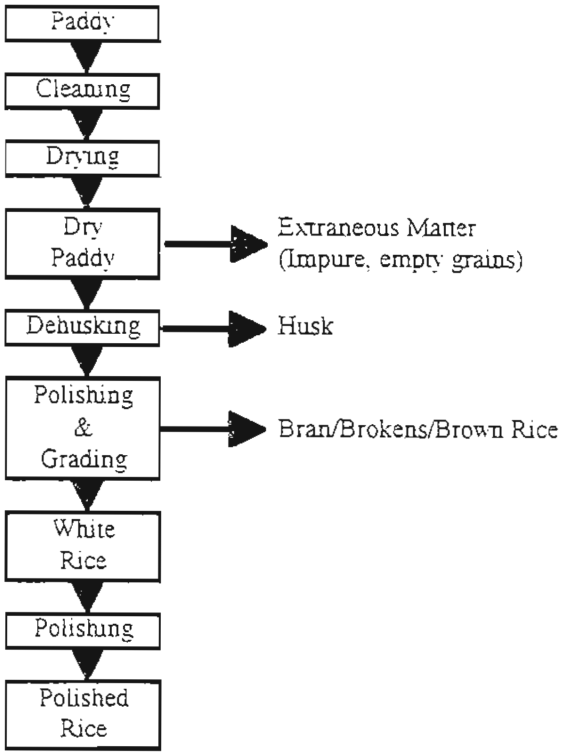

Figure 1 Milling process of the white rice mill

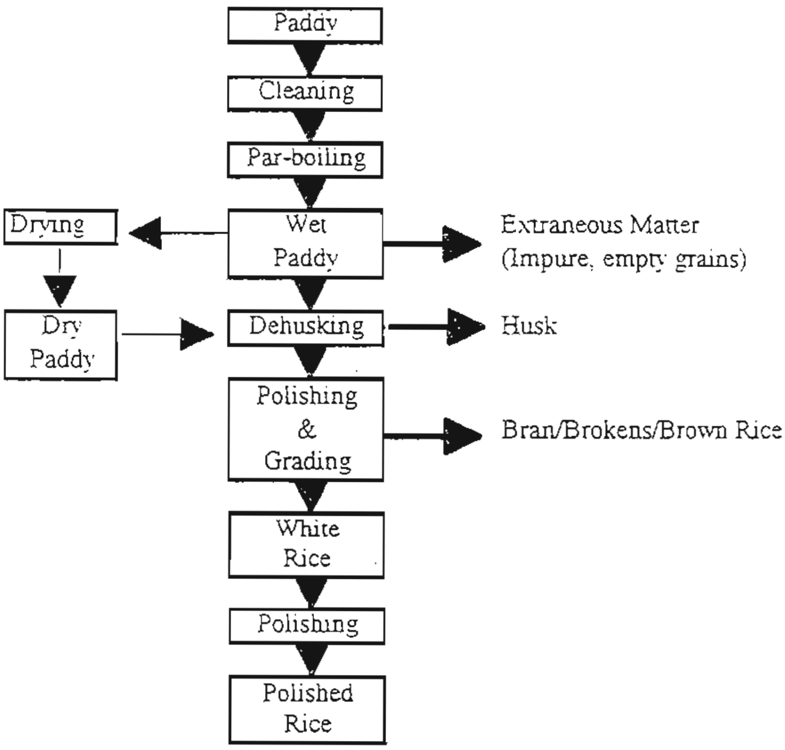

Figure 2 Milling process of the par-boiled rice mill

RESULTS AND DISCUSSION

Energy Consumption Analysis

From this study, it was found that electricity used for equipment in white rice mills and par-boiled rice mills were nearly the same. Total electricity used in white rice mill and par-boiled rice mill were approximately 190 MJ/ton paddy and 238 MJ/ton paddy respectively. From the analysis by saving thermal energy in paddy drying, it was found that thermal energy consumed in white rice mill was 242 MJ/ton paddy and thermal energy consumed in par-boiled rice mill was 1019 MJ/ton paddy of which 196, 150 and 673 MJ/ton paddy were used in soaking, par-boiling and paddy drying processes respectively.

From the comparative study, the electricity used for paddy husker in par-boiled rice mills was lower than that in white rice mills, as shown in Figure 3. It was because the husk of par-boiled paddy was more easily taken off. Electrical energy consumed in par-boiled rice mills was 5 and 7 MJ/ton paddy respectively whereas in white rice mill was 9 and 12 MJ/ton paddy. For the electricity used in rice whitening process, par-boiled rice mills consumed more energy than white rice mill. It was because the bran would more firmly attach to the grain. The electricity used for bucket, conveyor, sifters and bran collecting cyclone depended on the system design.

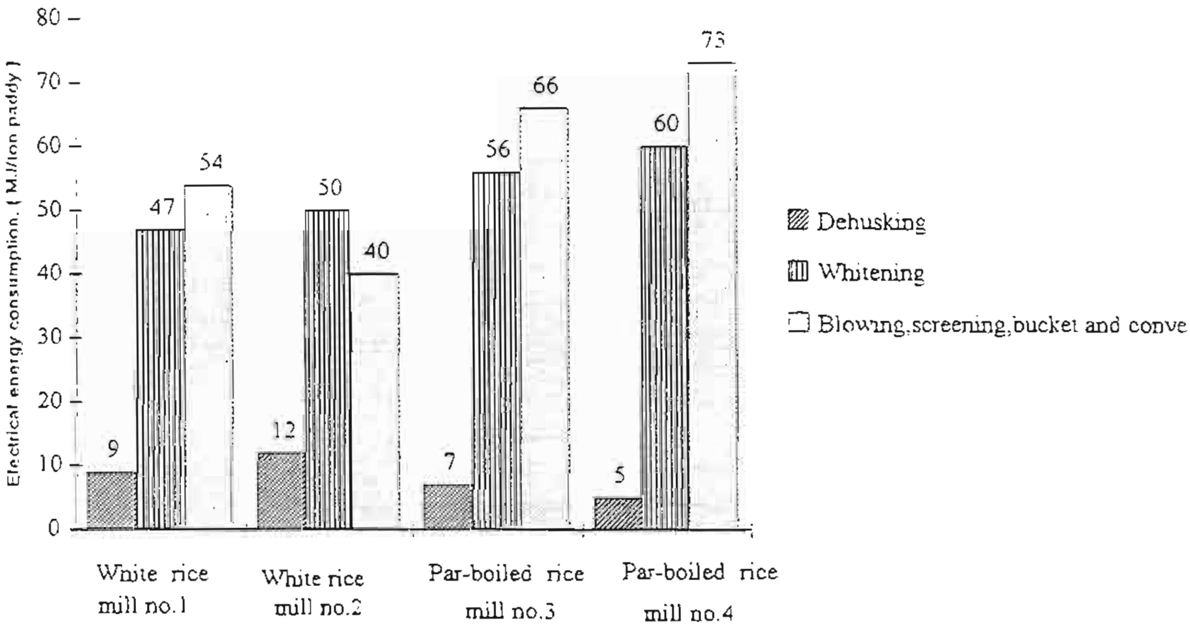

Figure 3 Comparison of eletrical energy consumption in rice milling process

Selection of equipment for cogeneration system

Gasifier with internal combustion engine

The analysis of cogeneration was based on using a combination of 160 kWh/unit gasifier with internal combustion engine produced in China. Total electricity generating by 260 white rice mills was 112 MW of which 97 MW was used in the mills and 15 MW was excessive. Heat generated could dry 50% of the total paddy to be milled. For 52 par-boiled rice mills, total electricity generated was 32 MW of which 28 MW was used in the mills and 4 was excessive. Heat from gasifier with internal combustion was not enough for heating process. Thus a boiler was needed to be added in order to generate heat for using in soaking and par-boiling processes. The heat obtained could dry 80% of the total paddy to be milled. Electricity and thermal energy generated in the system were shown in Table 1.

Table 1 Electricity and thermal energy generated in white rice mills and par-boiled rice mills by gasifier with internal combustion engine cogeneration system

Capacity tons/day	Number of rice mills	Electricity generation capacity kW/unit	Number unit	Total electricity generated kW	Electricity demand kW	Heat generated MJ/hr *	Heat demand MJ/hr
White rice mill							
124	199	160	2	320	274	1,313	1.250
226	39	160	4	640	499	2,627	2.279
336	11	160	5	800	742	3,223	3.388
563	11	160	8	1.280	1,243	5.253	5.676
Par-boiled rice mill							
135	28	160	3	480	371	5.227	5.307
223	15	160	4	640	604	15,727	9.466
320	9	160	6	960	867	20.307	13,587

* Heat generated did not pass through heat exchanger

The economic analysis showed that principle income of the rice mill was from the selling of husk ash.Currently, many rice mills sell husk ash to Germany at the price of 160 US$/ton husk. In this research, the husk ash price of 80 US$ /ton husk was used. If the rice mill did not obtain income from husk ash selling, return cost would be less than 25%, break even point was more than 4 years and electricity price was 0.104 US$/kWh. In the analysis, operating time was 270 days/year, interest rate was 16% /year and project life was 15 years.

Condensing steam turbine cogeneration

There are many types and sizes of commercial condensing steam turbine cogeneration. The proper selection of type and size of the condensing steam turbine cogeneration will maximize the return cost. The analysis of maximum return cost in order to select the appropriate size and number of steam boilers and steam turbines for cogeneration system was conducted. For husk ash price of 80 US$/ton , husk fuel price of 12 US$/ton and electricity purchasing price of 0.0348 US$/kWh, it was found that white rice mills with a capacity of 124, 226, 336 and 560 tons/day, the IRR were 27, 30, 33 and 36% respectively, and the generated electricity prices were 0.099, 0.086, 0.079 and 0.08 US$/kWh respectively. Par-boiled rice mills with a capacity of 135, 223 and 320 tons/day,the IRR were 33, 46 and 46% respectively, and generated electricity prices were 0.111, 0.104 and 0.094 US$/kWh respectively. In case of husk ash price of 0 US$/ton, the IRR was lower than 10%.

From the analysis, it was found that total electricity generated in 260 white rice mills was 150 MW of which 96 MW was used in the mills and 54 MW was excessive. Heat of flue gas from boiler was employed to be used in paddy drying process. The heat obtained could dry total of the paddy to be milled. Total electricity generated by 52 par-boiled rice mills was 29 MW of which 28 MW was used in the mills and 1 MW was excessive. Heat of flue gas from boiler, high pressure steam and condensate from condenser were employed to be used in soaking and par-boiling processes. The heat obtained could dry 78% of total paddy to be milled. Electricity and thermal energy generated by condensing steam turbine system of each mill were shown in Table 2.

Table 2 Electricity and thermal energy generated in white rice mills and par-boiled rice mills by condensing steam turbine

	White rice mill				Par-boiled rice mill		
Capacity (tons/day)	124	226	336	563	135	223	320
Electricity generated (kW)	396	883	1,297	1,980	386	616	966
Electricity demand (kW)	273	499	742	1,236	371	613	880
Heat produced (MJ/hr)*	2,760	5,031	7,377	11,968	6,774	11,634	16,374
Heat demand (MJ/hr)	1,250	2,279	3,388	5,676	5,307	9,468	13,587

*Heat generated did not pass through heat exchanger

Comparative cost of cogeneration systems

Gasifier with internal combustion engine cogeneration system is being developed for better efficiency and various capacities. This may reduce energy cost. The condensing steam turbine cogeneration system is popularly used due to various sizes to be selected for highest benefit. Details of the comparison were shown in Tables 3 and 4.

Table 3 Comparison of energy cost of gasifier engine system and condensing steam turbine system in white rice mill : working days of 270, husk fuel price of 12 US$/ton

White rice mill	Gasifier engine				Condensing steam turbine			
Capacity (ton/day)	124	226	336	560	124	226	336	560
Electricity used (kW)	274	499	742	1243	274	499	742	1,243
Electricity produced (kW)	320	640	800	1280	396	920	1,297	1,980
Cost of system (US$/kWe)	1,586	1,586	1,586	1,586	1,383	1,270	1,092	1,080
Cost of electricity (US$/kWh)	0.104	0.104	0.104	0.104	0.099	0.086	0.080	0.081

Table 4 Comparison of energy cost of gasifier engine and condensing steam turbine system in par-boiled rice mill : working days of 270. husk fuel price of 12 US$/ton

Par-boiled rice mill	Gasifier engine			Condensing steam turbine		
Capacity (ton/day)	135	223	320	135	223	320
Electricity used (kW)	371	613	880	371	613	880
Electricity produced (kW)	480	640	960	386	616	966
Cost of system (US$/kWe)	1,586	1,586	1,586	1,564	1,341	1.210
Cost of electricity (US$/kWh)	0.104	0.104	0.104	0.112	0.103	0.094

Reasonable price of purchasing electricity from the small-scaled producers

Electricity generating of 65.4 GWh by using hydrocarbon based fuel,i.e. fuel oil, diesel, natural gas and lignite, caused CO_2 emission of 43.59 M tons/ year (in fiscal year 1994). For total electricity generated of 69.85 GWh (using the four types of fuel including water power and geothermal power), the CO_2 was 0.63 kg/kWh. To reduce the amount of CO_2 emitted from using the four fuel each year by forestation, the area of forestation of 4.83 M hectare is needed. Average cost to reduce CO_2 is approximately 0.38 baht/kWh or 593 baht/ton CO_2 and thus the cost will increase electricity generating cost. Currently, the government encourages private sectors to generate electricity by biomass fuel, i.e husk, bargasse, etc. , and sell back to Electricity Generating Authority of Thailand (EGAT) in order to avoid the cost of electricity plants fabrication. CO_2 caused by biomass fuel can be recycled (the trees use CO_2 through photosynthesis process). Therefore, CO_2 does not accumulate in the atmosphere. In addition, husk fuel does not cause SO_2 as fossil fuel does. EGAT has installed flue gas desulfurization equipment with average economic cost of 0.15 baht/kWh. Consequently, EGAT should raise additional price of 0.38 baht/kWh or 0.53 baht/kWh to purchase electricity generated by using biomass fuel from private sectors.

CONCLUSION

From the analysis of energy consumption of the equipment in white rice mills and par-boiled rice mills , it could be concluded that electricity consumption in white rice mill and par-boiled rice mill were 190 MJ/ton paddy (53 kWh/ton paddy) and 242 MJ/ton paddy (66 kWh/ton paddy) respectively. Thermal energy consumption were 242 MJ/ton paddy in white rice mill and 1019 MJ/ton paddy in par-boiled rice mill. For using a 160 kW/unit gasifier with internal combustion engine from China in cogeneration system to maximize electricity generating, total electricity generated by 260 white rice mills was 112 MW of which 97 MW was used in the mills and 15 MW was excessive. Heat obtained could dry 50% of paddy to be milled. Total electricity generated by 52 par-boiled rice mills was 32 MW of which 28 MW was used in the mills and 4 was excessive. Heat obtained (a boiler was added) in a 223 tons/day capacity mill could dry 80% of the total paddy to be milled.

From the study of cogeneration using condensing steam turbine system, of which equipment were in various sizes, it was found that 260 white rice mills generated total electricity of 150 MW of which 96 MW was used in the mills and 54 MW was excessive. Heat obtained could dry the total paddy to be milled. Total electricity generated by 52 par-boiled rice mills was 29 MW of which 28 MW was used in the mills and 1 MW was excessive. Heat obtained could be used in soaking and par-boiling processes, and it could dry 78% of the total paddy to be milled.

Currently, the government encourages private sectors to generate electricity by using biomass fuel.i.e. husk, bargasse, etc. and sell back to EGAT in order to avoid cost of electricity plants fabrication. When combusted, biomass fuel causes CO_2. However, CO_2 can be recycled (the trees use CO_2 through photosynthesis process), thus CO_2 does not accumulate in the atmosphere. From the study, it was found that average cost in reducing CO_2 by forestation was 0.38 baht/kWh or 593 baht/ton CO_2. This expense makes electricity generating cost increase. In addition, EGAT also invested in installing flue gas desulfurization equipment to eliminate SO_2 at the cost of 0.15 baht/kWh. Consequently, EGAT should raise additional price of 0.38 baht/kWh or 0.53 baht/kWh to purchase electricity generated by using biomass fuel from private sectors.

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EVALUATION IN PRODUCT QUALITY OF IN-STORE CORN DRYING

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ABSTRACT

The aim of this research is to study the feasibility of in-store corn drying. Both economics and acceptable corn quality are taken into consideration. Some parts of this research, energy consumption and corn quality, are presented in this paper. The equipment had been installed at Pra Buddha Baht Settlement Agricultural Cooperatives. Ambient air flow rate of 5.44 m^3/min-m^3 of corn was ventilated through a 30 t capacity corn bulk of which initial moisture content was 19 % wet-basis. The experimental results showed that aflatoxin B-1 production during the experiment was completely inhibited as compared to that at the beginning of corn drying even if the number of corn kernels infected with *Aspergillus flavus* increased. In decreasing moisture content of corn from 19 % wet-basis to 12.5 % wet-basis, electricity consumption was 15 kW-h/t of corn (US$ 0.9/t of corn).

INTRODUCTION

At the present , nearly all most of corn produced has been used in feed mill industry and also still played an important role for Thai people for many years. From a research report (Kositcharoenkul et al., 1992), it was evidenced that corn, which was freshly harvested and then stored in the barns or silos of merchants, would be infected with *Aspergillus flavus* producing aflatoxin substance. Aspergillus flavus's growth rate increases rapidly if corn is stored in unsuitable condition under hot and humid climates. Aflatoxin is very toxic to human health and animals. Therefore, a quantity of aflatoxin contamination in food for animals is not allowed more than 20 μg/kg (USA). Aflatoxin contamination is often detected in freshly-harvested corn during rainy season. This is because moisture reduction in corn by sun drying on a concrete pad is not available. However, this problem can be solved by using mechanical drying or in-store drying technique.

Morey et al. (1978) studied the energy consumed for corn drying in a bin with a dimension of 5.5 m diameter and 4.5 m high. The experimental results showed that in reducing moisture content of corn from 28 % wet-basis to 24 % wet-basis using 120 °C inlet hot air temperature and a 120 m^3/min-m^3 of corn air flow rate and then continually dried to 15 % wet-basis using ambient air, the energy consumed was minimized.

Shove (1984) studied the energy consumption for corn drying with low drying air temperature. It was found that energy consumption was 6 kW-h/t-percentage of water evaporated in reducing moisture content of corn from 22 % wet-basis to 15 %

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using a 2 - 4.5 m^3/min-t of corn air flow rate. However, when ambient air was heated in a few degrees, energy consumption increased to be 12 kW-h/t-percentage of water evaporated using a 0.8 - 2.2 m^3/min- t of corn air flow rate.

Eckhoff et al. (1984) investigated the inhibition of microorganism growth rate using gas mixture, sulfur dioxide mixed ambient air. Mixed gas was flowed through the corn bulk, which was stored in a bin with 5 t capacity. Initial moisture content of corn was 28 % wet-basis. From the experimental results, it was found that when mixed gas was flowed from the top of the bin to the bottom of the bin, the number of microorganisms was very small but when mixed gas was flowed inversely in the direction with mentioned before, microorganisms spread widely at the top area, where moisture content of corn was rather high. In case of corn fumigated with sulfur dioxide gas before loading into the bin, a large extent of microorganisms distributed throughout the bin. Moreover, percentage of stress-cracked corn using sulfur dioxide gas was lower than that using hot air temperature.

El-Gazzar and Marth (1988) carried out the effect of hydrogen peroxide concentration on the aflatoxin production and the growth rate of *Aspergillus parasiticus*. 10^6 *Aspergillus parasiticus* spores was inoculated on a glucose-yeast-salt medium and then was incubated at temperature of 14 and 28 °C in 90 days. It was found that *Aspergillus parasiticus* growth and aflatoxin production was not produced at 0.3 and 0.5 % hydrogen peroxide concentration.

Nilrattanakorn et al.(1994) studied the optimum rate of carbon dioxide fumigation for controlling *Aspergillus flavus* growth and aflatoxin production at high moisture content of corn. Corn had been fumigated for 4 days at rates of 0.5, 0.75, 1.0 and 2.0 kg CO_2/t of corn. It was found that 0.5 kg CO_2 /t of corn rate of carbon dioxide fumigation could prevent the aflatoxin and the *Aspergillus flavus* growth effectively. For storing corn without ventilating air and carbon dioxide fumigation, nearly all of corn bulk was infected with *Aspergillus flavus*. Also, aflatoxin contamination and temperature in corn bulk increased.

Wongurai et al.(1992) conducted experiments to study the effect of water activity on *Aspergillus flavus* growth in corn. It could be concluded that *Aspergillus flavus* growth was severely infected at 0.94 - 1 water activity at 28 °C temperature, corresponding to 22 - 41 % wet-basis equilibrium moisture content. However, when water activity was less than 0.85 at 28 °C temperature, corresponding to moisture equilibrium lower than 18 % wet-basis, *Aspergillus flavus* growth was inhibited completely.

Prachayawarakorn et al. (1995) studied the prevention of aflatoxin production in in-store corn drying. The experimental results showed that high moisture content of corn should be dried to 18 - 19 % wet-basis within 2 days and then continually dried to 12-13 % wet-basis within 14 days in order to prevent aflatoxin production. In reducing moisture content of corn from 19 % wet-basis to 12 -13 % wet-basis using a 3.6 - 4.6 m^3/min-m^3 of corn ambient air flow rate, energy consumption was 10-11 kW-h/t of corn (US$ 0.6 - 0.7 /t of corn).

From the researches outlined above, it was rather clear that microorganism growth and aflatoxin production were in large quantities at the conditions of both high moisture content of grain and high relative humidity of ambient air. In order to control aflatoxin and microorganisms, chemical substances should be applied in a range of high moisture level. In case of moisture content lower than 20 % wet-basis, in-store drying technique with ambient air was rather effective. Therefore, this research is to study feasibility of in-store corn drying system under tropical climate. Both economics and corn quality will be considered. Some parts of this research, energy consumption and corn quality. are presented in this paper.

MATERIALS AND METHODS

Equipment

A dimensional area for 30 t capacity of corn was 5 m wide, 5 m long and 1.5 m high. Air ducts are principally composed of main ducts (No 1-6) and branching ducts (No 7-9, 10-12 and 13-15) as shown in Figure 1. The 0.4 m X 0.4 m cross sectional area in each main duct was made by galvanized steel sheets with 1.5 mm thickness. Each branching duct is made from 3 semicircular ducts. A semicircular duct, made from 1.5 mm thickness perforated steel sheets with 1.5 mm diameter holes, is 1.20 m long and 55 cm diameter. A backward curved blade centrifugal fan was driven by a 3.7 kW motor.

Experiment

Ambient air flow rate of 5.44 $m^3/min\text{-}m^3$ of corn at 35 °C temperature and 55 % relative humidity was blown through the corn bulk of which initial moisture content was 19 % wet-basis. In addition to measurement of wet-bulb and dry-bulb temperature of ambient air, temperature in corn bulk was also measured at 2 positions, 3 points each position. Temperatures were measured by type K thermocouple from which measurements were transferred to a data logger (accuracy of ± 1 °C). To check the moisture content of corn during experiment, corn samples were collected at the depths of 0 m, 0.30 m, 0.75 m and 1.20 m from the surface. However, for testing corn quality, corn samples taken from 0.75 m and 1.20 m depths from surface were detected the quantities of aflatoxin B-1 by thin layer chromatography method and also determined the number of corn infected with *Aspergillus flavus*.

To determine the moisture content of corn, corn samples were placed in a hot air oven at a fixed temperature of 103 °C for 72 hours. To test aflatoxin B-1 and *Aspergillus flavus* infected , corn samples of which moisture content was higher than 14 % wet-basis must be dried to 14 % wet-basis and then stored in a temperature - controlled room in which temperature was lower than 10 °C.

RESULTS AND DISCUSSION

Temperature

Temperature in corn bulk is a significant factor which affects on corn quality : due to great temperature gradient in corn bulk, the natural air recirculation will occur and consequently water vapor in air will condense while air flows against corn of which temperature is rather low. Therefore, microorganism growth increases rapidly in areas of high moisture level. Figure 2 shows the evolution of ambient air temperature and temperature in corn bulk. It was found that temperature in corn bulk was lower than ambient air temperature flowing through the corn bulk and rather insignificantly different throughout the corn bulk. Temperature varied between 26 °C and 28 °C, which was suitable for producing aflatoxin B-1 by *Aspergillus flavus* (Koehler et al., 1985).

Moisture Content

During 20 day drying time with ambient air ventilation, 8 hours each day, moisture content of corn reduced from 19 % wet-basis to 12.5 % wet-basis. Figure 3 shows that moisture content of corn at deeper depth from surface was lower than that at lower depth from surface. This is because the amount of water vapor in air flowing from the bottom region to the top region increases with direction of air flow. Consequently, moisture reduction at the top region was rather lower as compared to that at the bottom region. However, at the end of drying, moisture content of corn throughout the corn bulk was nearly the same because of movement of drying zone from the bottom area to the top area.

Energy Consumption

In reducing moisture content from 19 % wet-basis to 12.5 % wet-basis using a 5.44 m^3/min-m^3 of corn ambient air flow rate, energy consumption in terms of electricity was 15 kW-h/t of corn (US$ 0.9 /t of corn).

Corn Quality

Figure 4 shows the evolution of aflatoxin B-1 and average moisture content of corn during corn drying. It was found that the quantities of afltoxin B-1 detected at each depth were rather uncertain. The researchers in the field of microtoxins suggested that each corn kernel must be taken to detect aflatoxin B-1 in order to make sure in quantities of aflatoxin B-1 produced. However, it is impossible in practice. Therefore, the average quantities of aflatoxin B-1 were substituted for the quantities of aflatoxin B-1 throughout the corn bulk. The results showed that the quantities of aflatoxin B-1 at the beginning of drying were nearly equal to those at the end of drying while the number of corn kernels infected with *Aspergillus flavus* increased as shown in Figure 5. It might be explained that *Aspergillus flavus* growth did not affect on aflatoxin B-1 production.

CONCLUSIONS

The experimental results could be concluded as follows :

1. For in-store corn drying with ambient air flow rate, the corn quality in terms of aflatoxin B-1 production at the end of drying could be maintained even though the number of corn kernels infected with *Aspergillus flavus* increased.
2. When corn was dried from 19 % wet-basis to 12.5 % wet-basis using 5.44 m^3/min-m^3 of corn, electricity consumption was 15 kW-h/t of corn (US$ 0.9 /t of corn).

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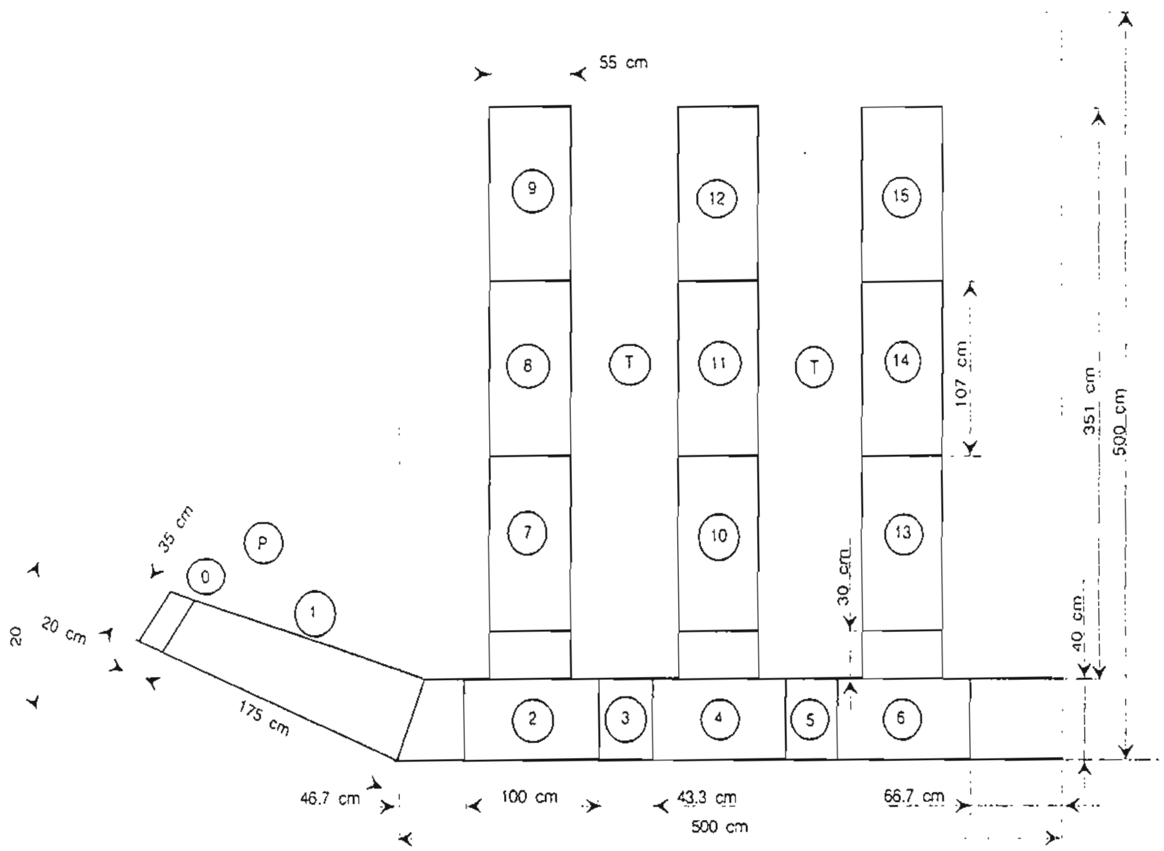

Figure 1 Plan of ducts on floor showing positions of temperature and pressure sensors.

0 = flexible duct
1,2,3,4,5,6 = main ducts, 40 cm x 40 cm
7,8,9,10,11,12,13,14,15 = perforated branching ducts, 55 cm
T = temperature
P = pressure

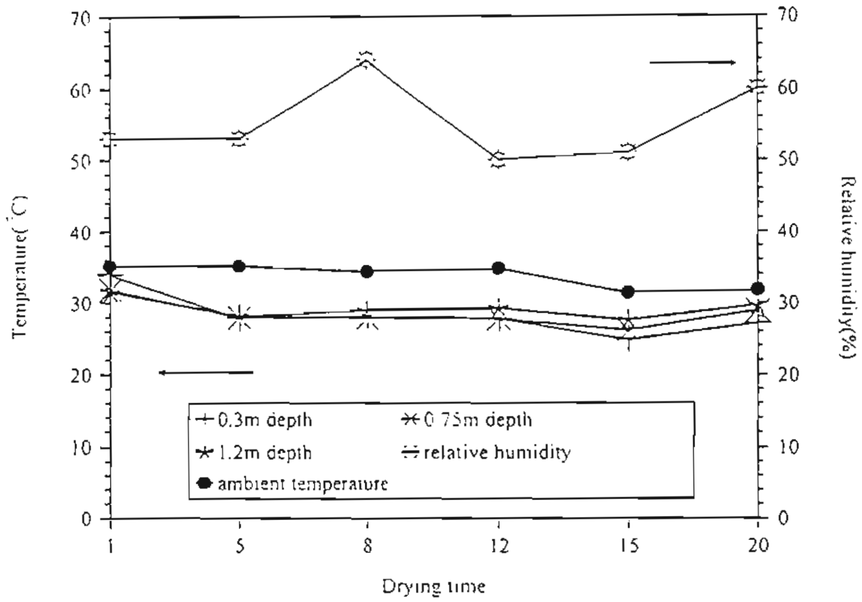

Figure 2 Evolution of temperature in corn bulk and ambient air temperature and relative humidity

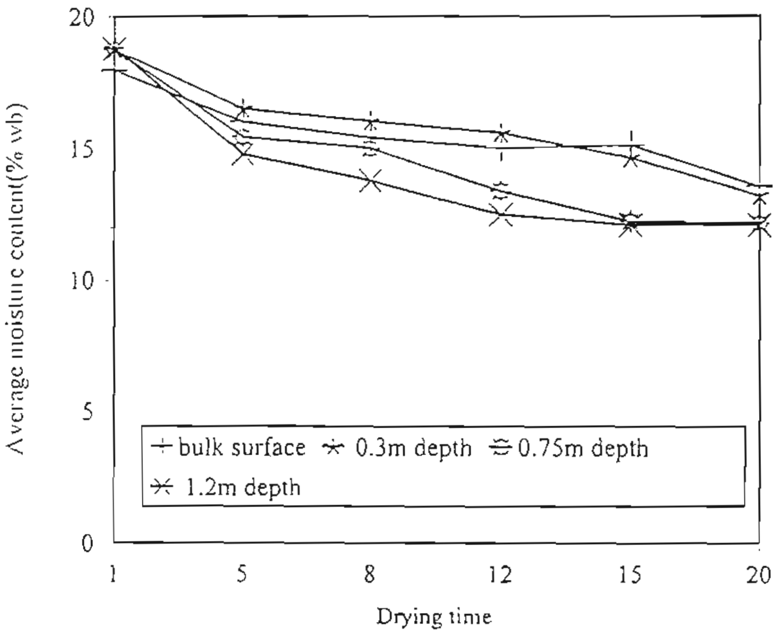

Figure 3 Evolution of corn moisture content at different depths

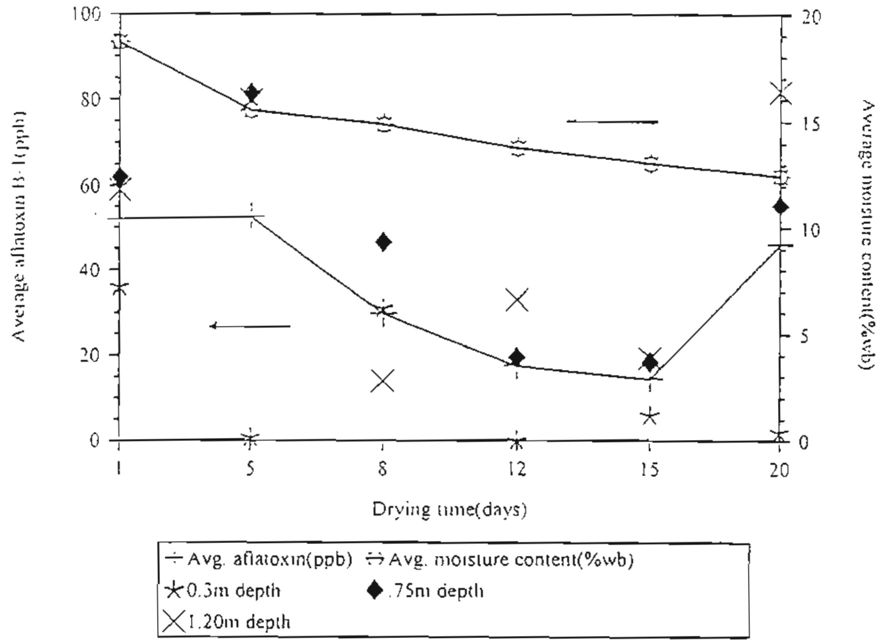

Figure 4 Evolution of average aflatoxin B-1 and average moisture content of corn
{moisture content of corn reduced from 19 % to 12.5 % wet-basis}

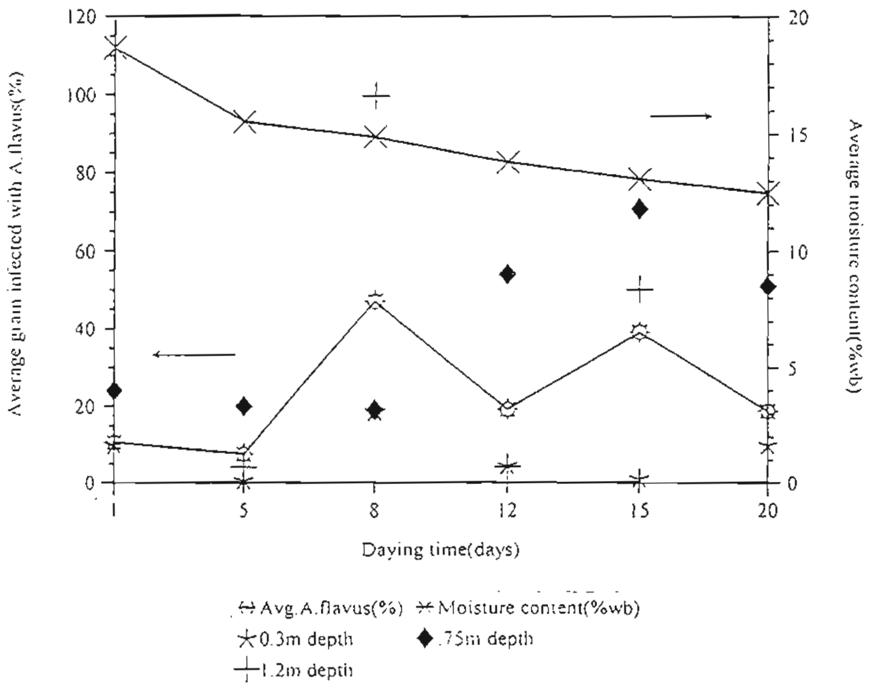

Figure 5 Evolution of average moisture content and average grain infected with A.flavus at different depths
{moisture content of corn reduced from 19 % to 12.5 % wet-basis}

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STUDY OF AN INDUSTRIAL SCALE SOLAR DRYING SYSTEM FOR BANANA

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ABSTRACT

The objectives of this research are to study a solar banana dryer for determining the performance of 4 types of solar air heater absorbers, which contain approximately 21.3 m^2 of collector surface area each, and also the performance of a solar banana dryer from solar energy and LPG in an industrial scale. All the economical probabilities of the system are also analyzed.

From the results, it was determined that the thermal efficiency of the corrugated absorber plate which employed thermax insulation (poly-isocyanurate), and the finned absorber with the same insulation delivered the highest efficiency of 41.0% and 38.8% respectively. The flat plate absorber with thermax insulation, and the flat plate absorber with polyurethane foam delivered the maximum efficiency of 31.6% and 32.1% respectively. The results of drying bananas determined that the moisture could be reduced as required. Drying time for each batch of cycle drying was 5 days (44 hours/batch). The energy consumption of the dryer was 14.9 MJ/kg water evaporated. The maximum efficiency of the first Thermodynamics law of the drying system was about 30.5% (average 15.5%). From the economical analysis, it was found that payback period varied from 3.2–4.7 years.

INTRODUCTION

Drying is one process of food preservation that Thai people have extensively applied to agricultural crops, to provide added value to the produce. Various drying technologies have been recently applied in drying processes, to ably assist in the reduction of operational expenses. The use of solar energy is one example, but the technology still requires further development to prove appropriate for a broader range of drying applications. The region of Phitsanulok and surrounding districts have a considerable amount of "nam-wa" bananas which are commonly dried by open-sun drying, thus exposed to dust, insects, mould and micro-organisms, further creating product quality problems. These problems could be reduced by using an effective solar dryer.

Prida Wibulswas et al. [1] determined the drying rate of damp cloth (dipped in water) at 4.2 kg/m^2-day, by using a solar dryer that permits natural convection of thermal air. Prida Wibulsawas and Thaina [3] tested a hybrid solar dryer that naturally convected air to procure a drying rate of 5 kg/m^2-day for damp cloth. Excell [2] developed a solar dryer for paddy rice

Key Words : Solar Energy, Solar Dryer/Dried bananas/Drying/Solar Collector

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that employed natural convection to achieve a drying time of 2-3 days. Furthermore, research was conducted to develop a model dryer that employed forced convection of thermal air, generally used for grain drying, as reported by Soponronnarit et al. [5]. Soponronnarit and Tiansuwan [6], Soponronnarit and Tiansuwan [7] ,and Boonlong et al. [8] studied tobacco barn-drying by using solar energy, followed-up by Sitthipong et al. [9], who modified the drying barn to dry various fruits. Additional information is available in literature published by Soponronnarit [10] and Soponronnarit [11]. Other than these findings, Ong [4] concluded the achieved research results and developments concerning solar dryers from various Asian countries. Wattanapong et al. [12] studied a hybrid solar dryer for "namwa" bananas, that used forced convection by means of an exhaust fan drawing thermal heat from a solar collector via a heat exchanger, prior to entering the drying chamber. The static efficiency of the solar drying system is according to the average moisture content of the banana, delivering an optimum efficiency of 30% and further showed a return on investment between 1.5-5.4 years.

Through observing various projects within Thailand, it could be concluded that the use of a solar dryer (natural convection) for bananas is economically feasible (Patranon,[13]), and forced convection is also seen as feasible technology (Soponronnarit et al. [14]). Therefore the latter should be appropriate for small-scale industries, due to the ability to be conveniently combined with other energy sources, and having high air-flow rates to record satisfactory drying rates and efficiencies.

The "ASEAN-Canada Project on Solar Energy in Drying Processes developed a solar dryer for "nam-wa" bananas, with the capacity to batch process 500 kg of fresh bananas per drying chamber. The solar collector incorporates three different designs and has an auxiliary heating source. The drying system was recently constructed at Bangkrathum, Phitsanulok. This research has the objective to develop an acceptable solar dryer model for commercial dissemination. All the economical probabilities of the system are also analyzed.

MATERIALS AND METHOD

1. Design:

The solar dryer force convects thermal air and has various solar collector units that are separated from the drying chambers. The heat transfers through the collectors within the air-flow in flow channel to later exit at collector outlet.

For times of insufficient ambient temperatures, LPG will be a stand-by auxiliary, that directly heats ambient air in a junction burner located near the exhaust fan. One drying system comprises of 23.5 m^2 of solar collector area and a drying chamber 2m x 2m x 6m long, that accommodates three trolleys, five drying shelves, and sixty drying trays. Under operating conditions the working air passes through the solar collector and directly enters the drying chamber through four perforated ducts located on the chamber floor. The air is further convected vertically, working over the drying bananas to ultimately exit at the chamber roof through six outlets.

2. Testing :

2.1 The testing of solar collector was as follows

- Air Flow Rates: determined by the average air velocity of exhaust air at the cross-section of the air duct with a fan anemometer.
- Temperature: entering and exiting solar collector, by using a thermometer with a degree of acuracy $\pm$ 0.5°C, and recording at one hour intervals.
- Total Solar Radiation: receieved on the solar collector surface, by using a solar indicator with a degree of accuracy $\pm$ 5%; and a pyranometer with a degree of accuracy $\pm$4%.
- Air velocity above the solar collectors: determined by using a digital anemometer, model DA- 42 with a degree of acuracy $\pm$2%

The comparison of the solar collector performance between the experiment and the theory is also included.

2.2 The testing of the drying system used 360 kg of peeled banana weight. During the daytime solar energy was employed, and LPG through 9.00-11.00 am and 4.00-8.00 pm in the first day. The bananas were covered with plastic each night to undertake sweatening. After the fourth day of drying the bananas were flattened and further dried for another one day, to achieve a total final moisture content weight of 141.1 kgs. The drying test collected the following data.

- Electrical consumption: of the centrifugal fan measured with a Camp amp meter (Yokogawa), degree of accuracy $\pm$ 0.1%, and recording at one hour intervals.
- Temperature inside drying chamber at 10 various positions points by using type-K thermocouple connected with Data Logger, Model 3750 HR1300 with a degree of accuracy 1%.
- Moisture content of the product: by random selection of banana samples, weighed by accurate scales, then cut into small pieces and oven dried at 103°C for 72 hours.
- Water evaporation:by using large scales (Max.cap.60 kg), with a degree of accuracy $\pm$0.1 kg and record weight changes before and after each drying period.
- Total solar radiation: received on the solar collector surface, by using a solar indicator with a degree of accuracy $\pm$ 5%.
- LPG consumption: determined by recording LPG weight displaced.

RESULTS

1. Results of Collector Testing:

Upon testing the performance of the solar collector, recordings of various values were logged hourly during the drying times of 9.00-16.00, thus determined the data as follows.

1.1 The solar collector that incorporated the flat-plate absorber (23.1 m^2) with polyurethene foam insulation resulted with a 29.7°C inlet temperature; 53.5 °C outlet temperature; 27.5°C ambient temperature, 804-883 W/m^2 of total solar radiation; and air flow rates at 0.26 kg/s. The maximum efficiency of the collector was 32.1%.

1.2 The solar collector that incorporated the flat plate absorber (23.1 m^2) with polycyanurate(thermax) insulation resulted with a 29.9°C inlet temperature; 50.5°C outlet temperature; 29.3°C ambient temperature, 631-790 W/m^2 of total solar radiation; and air flow rates at 0.26 kg/s. The maximum efficiency of the collector was 31.6%.

1.3 The solar collector that incorporated the corrugated absorber (23.1 m^2) with polycyanurate (thermax) insulation resulted with a 30.7°C inlet temperature; 54.8°C outlet temperature; 29.9°C ambient temperature, 751-786 W/m^2 of total solar radiation; and air flow rates at 0.28 kg/s. The maximum efficiency of the collector was 41%.

1.4 The solar collector that incorporated the finned absorber (23.2 m^2) with polycyanurate (thermax) insulation resulted with a 30.2°C inlet temperature; 57.8°C outlet temperature; 30.1°C ambient temperature, 776-892 W/m^2 of total solar radiation; and air flow rates at 0.26 kg/s. The maximum efficiency of the collector was 37.4%.

2. Test Results of Drying Bananas:

The average amount of peeled bananas in used are 360 kg, and reduced to dried bananas approximately 141.1 kg every day.

The data from May 15-19,1995.

1. Initial weight of bananas (peeled) prior to drying	360.0 kg
2. Final weight of bananas after drying	141.1 kg
3. Water evaporation loss	218.9 kg
4. Total solar radiation at collector surface	1814.9 MJ
5. Total drying time with solar energy	27.0 hours
6. Total drying time with LPG	17.0 hours
7. Total LPG consumption	21.2 kg
8. Total electrical comsumption of fan	393.8 MJ
9. Total energy consumption of LPG (17 hours)	1060.4 MJ
10. Total energy consumption of solar	1814.9 MJ
11. Total amount of energy consumed	3269.1 MJ
12. The latent heat	2.4 MJ/kg
13. 1st Law thermodynamic efficiency	= [(218.9x2.4)/3269.1]x100 = 16.1%
14. Specific energy consumption	= 3269.1/218.9 = 14.9 MJ/kg water evaporated
15. Specific solar energy consumption	= 1814.9/218.9 = 8.3 MJ/kg water evaporated
16. Specific electricity consumption	= 393.8/218.9 = 1.8 MJ/kg water evaporated
17. Specific LPG consumption	= 1060.4/218.9 = 4.8 MJ/kg water evaporated

From the test conducted, it was determined that the fresh banana has an initial moisture content of 288.8 %db, and a final moisture content upon drying of 47.3 %db. The maximum efficiency of the first thermodynamics law of the drying system was about 30.5% (average 15.8%). The total amount of energy consumed was 3269.1 MJ, comprising of 8.3 MJ/kg-water evaporated from solar energy(55.7%), 4.8 MJ/kg-water evaporated from LPG(32.1%), and 1.8 MJ/kg-water evaporated from electricity(12.1%).

ECONOMICAL ANALYSIS

The construction cost of the solar dryer is 1,994,731 Baht.The amount of dried bananas from cycle drying are 56,012 kg. It can make the income 1,876426 Baht per year,and the operating and the maintenance cost is estimated to be about 1,255,495 Baht per year. By assuming the discount rate at 15 %, the benefit cost raito is 1.6, the internal rate of return is 29.1 %, the payback period is 3.2 years and the discount payback period is 4.7 years. (Estimate at 3 Bath per kilogram of fresh banana ,2.53 Baht per unit of electricity cost, 12 Baht per kilogram of LPG and 33.50 Baht per kilogram of dried bananas.)

CONCLUSION

1. The test determined that the performance of the corrugated absorber with Thermax, and the finned absorber with thermax,will both deliver higher efficiencies at 41% and 38.8% respectively, due to having greater area of heat transfer and higher diffuse radiation receiving area. The efficiencies of the flat-plate absorber with polyurethene foam and thermax were lower at 32.7 and 35.4% respectively.
2. The insulation materials of polyurethene and polycyanurate(thermax) delivered indifferent efficiencies within the respective collector designs.
3. From the comparison between the experiment and theory by computer programming show that the efficiency of the flat-plate absorber with polyurethane foam is 51.2% however showing 32.1% from the experiment (19 % different). The efficiency of the flat-plate absorber(with thermax) is 31.6 % but 53.2 % from the computer programming (21.6 % different).Because there was some This variation was due to possible error readings and som leakages at the connections delivering higher absorbtivity, transmissivity, collector radiation, cover radiation values during all temperature measurment.
4. The drying time was 5 days per batch (44 hours). The color of dried bananas is darker than open sun dried bananas, hower having a sweeter taste.
5. The results showed that the solar dryer is able to reduce the moisture content to the required degree. Solar energy consumption of the dryer is 14.9 MJ/kg-water evaporated; the auxiliary energy consumption is LPG at 4.8 MJ/kg-water evaporated; and the electrical blower energy at 1.8 MJ/kg-water evaporated.

RECOMMENDATION

There should be more performance testing conducted to determine uniform heat distribution within the drying chamber under working load conditions. The hot air recycle system and the suitable LPG burner should be used for heat loss reducing.

ACKNOWLEDGEMENT

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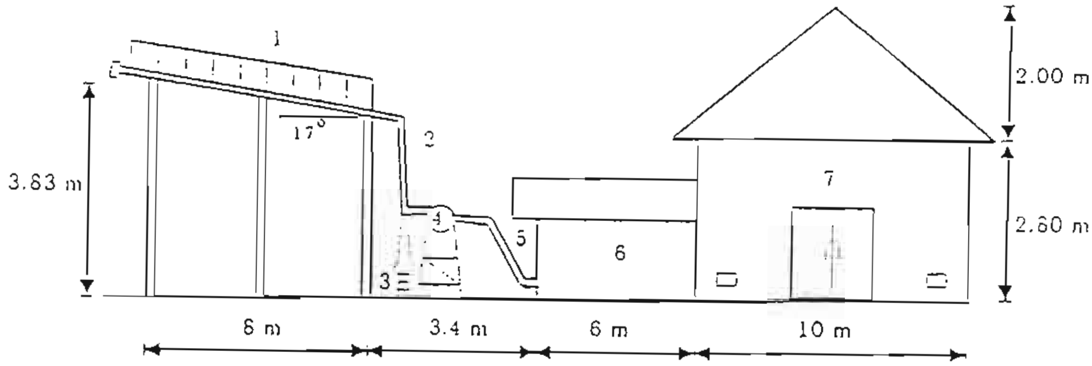


1. Solar Collector
2. MainFolding
3. Burner Stove
4. Blower
5. Ducting
6. Cabinet Dryer
7. Facilitaing Room

Fig. 1 The component of solar dryer system

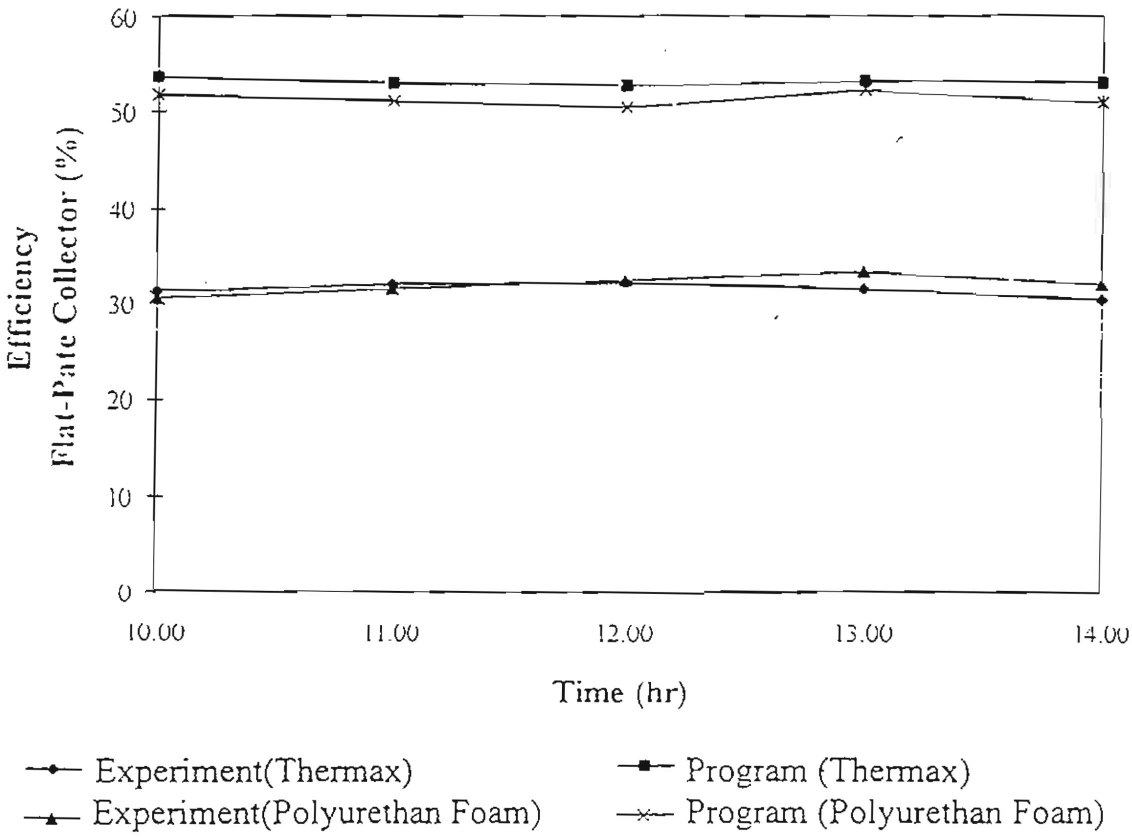


Fig. 2 Daily efficiency of solar flat plate collector from the experiment and computer programming

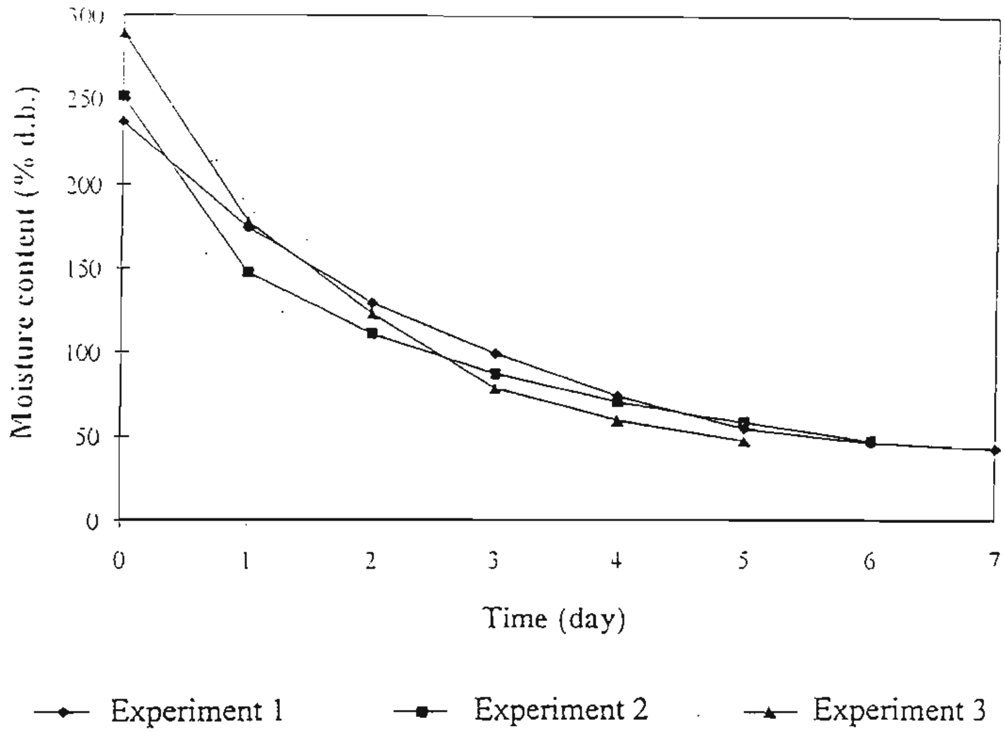
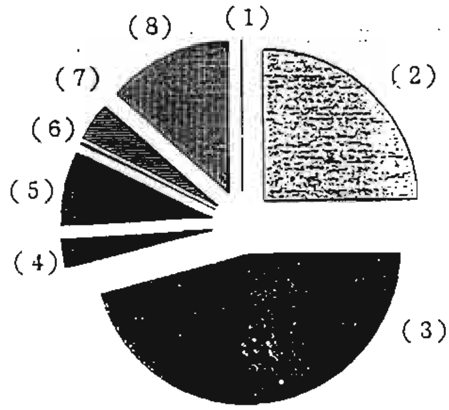


Fig. 3 Relation of moisure content and drying time



(1)	Land cost	(2)	Wage
(3)	Banana cost	(4)	Electricity cost
(5)	LPG cost	(6)	Maintenance cost
(7)	Operating cost	(8)	Packaging cost

Fig. 4 Anual cost for economical analysis

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PROGRESS IN COMMERCIALIZATION OF FLUIDIZED BED PADDY DRYER

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Key Words : drying ; fluidization ; grain

ABSTRACT

Technology of fluidized bed grain drying has been introduced since the past 20-30 years. The fluidized bed grain dryer was, however, not commercially successful. In this paper, the concept of continuous cross-flow fluidized bed paddy dryer is described. It is now fully commercialized in Thailand. More than 60 units are available in private rice mills and more than 10 were exported (as of November 1996).

Reasons for supporting successful commercialization may be due to :
1. Recycling of exhaust air which reduces energy consumption significantly
2. Very high capacity due to possible use of very high temperature of drying air and finally
3. Very close collaboration among the research team of King Mongkut's Institute of Technology Thonburi, a private manufacturer of drying equipment and a private user.

Performance evaluation of commercial fluidized bed paddy dryers indicated that energy consumption per kilogram of water evaporated decreased with increasing moisture level of paddy and drying air temperature. It is recommended for drying paddy from any moisture level down to 22 % dry-basis in a single pass that drying air temperature may be up to 150 °C with acceptable product quality.

INTRODUCTION

Paddy combined harvester is becoming popular in Thailand especially in the central and lower north of Thailand. Consequently, the problem of high moisture grain is now very serious. Rice mills are responsible for the problem due to high competitiveness and therefore are looking for appropriate methods of drying. It has been suggested that high moisture paddy should be dried quickly down to approximately 23 % dry-basis then followed by ambient air drying in storage (Soponronnarit et al., 1994. Driscoll and Srzednicki, 1989). Following the two-stage drying, cost and product quality seem to be optimized. During the first stage, fluidized bed drying is an alternative to conventional hot air drying. Its advantages are (1) uniform product moisture content, as a result, high air temperature can be employed due to less overdried grain, (2) high drying capacity due to better heat and mass transfer and (3) much smaller drying chamber which results in much lower initial cost.

Soponronnarit and Prachayawarakorn (1994) reviewed some research and development works on fluidized bed drying of grain. Little progress was observed during the past few years especially drying of paddy with fluidization technique. Soponronnarit and Prachayawarakorn (1994) also conducted both experimental and simulated work on fluidized bed paddy drying in batch. The results showed that maximum drying air temperature had to be limited to 115 °C and final moisture content of paddy at 24-25 % dry-basis if product quality in terms of head yield and whiteness was maintained. To maximize drying capacity and minimize energy consumption, air velocity of 4.4 m/s, bed thickness of 9.5 cm (corresponding to specific air flow rate of 0.1 kg/s-kg dry matter of paddy) and fraction of air recycled of 80% should be employed. Specific energy consumption in terms of primary energy which was equal to heat plus 2.6 times electricity was reported at approximately 7.5 MJ/kg-water evaporated.

Soponronnarit et al. (in press) described the development of a cross-flow fluidized bed paddy dryer with a capacity of 200 kg/h. Experimental results showed that final moisture content of paddy should not be lower than 23% dry-basis if quality in terms of both whiteness and head yield was maintained. Drying air temperature was 115 °C. Simulated results indicated that the appropriate operating parameters should be as follows: air speed of 2.3 m/s, bed thickness of 10 cm and fraction of air recycled of 80%. At this condition, energy consumption was close to the minimum while drying capacity was near the maximum. In this study, moisture of paddy was reduced from 30% to 24% dry-basis.

According to the success of the development of the cross-flow fluidized bed paddy dryer, Rice Engineering Supply Co. Ltd., a private company based in Thailand, showed his interest in the collaboration of the development of a prototype with a capacity of approximately 1 ton per hour (Soponronnarit et al.,1995). Figure 1 shows the prototype fluidized bed paddy dryer. It comprises of a drying section, a 7.5 kW backward curved blade centrifugal fan, a diesel fuel oil burner and a cyclone. The bed length, width and height of the drying section are 1.7 m, 0.3 m and 1.2 m respectively. Experimental results showed that the unit operated efficiently and yielded high product quality in terms of head yield and whiteness. In reducing the moisture content from 45% to 24% dry-basis using air temperature of 100-120 °C, fraction of air recycled of 0.66, specific air flow rate of 0.05 kg/s-kg dry matter, superficial air velocity of 3.2 m/s, bed depth of 0.1 m, total primary energy consumption was 1.86 MJ/kg-water evaporated of which 0.36 was primary energy from electricity (electrical energy multiplied by 2.6) and 1.5 was primary energy in terms of heat.

According to the success of the prototype, commercial fluidized bed paddy dryers with capacity of 5 tons/h and 10 tons/h are now available. More than 60 units have been sold since the beginning of 1995 (as of November 1996).

The objective of this paper is to describe the performance of commercial fluidized bed paddy dryers. Paddy quality and energy consumption are discussed.

MATERIALS AND METHODS

Operation of fluidized bed dryer

The fluidized bed dryer, as shown in Figures 1-2, is mainly composed of a drying chamber, a backward curved blade centrifugal fan, a burner using diesel oil or fuel oil for heating air and a cyclone. Paddy is fed in and out by rotary feeders. Paddy bed depth is controlled by a weir. In operation, paddy flows in perpendicular direction to the flowing inlet air of which temperature is controlled by a thermostat. A small part of the exhaust air is delivered to atmosphere.The rest of exhaust air flows through the cyclone. Then it is recycled, mixed together with ambient air at a combustion chamber and reheated to a desired temperature. It is also possible to deliver the exhaust air after the cyclone. Three models of commercial fluidized bed paddy dryer are available , 1.0-2.0 tons /h, 2.5-5.0 tons/h and 5-10 tons/h.

Methods of experiment

In this work, results were obtained from several sites where the fluidized bed dryers with different capacity had already been installed. With a 1-2 ton/h capacity fluidized bed dryer, inlet air temperature varied from 60°C to 120 °C, air flow rate was 1.6 m^3/s, corresponding to a superficial air velocity of 3.13 m/s measured by a hot wire anemometer, and initial moisture content of paddy varied from 27 % to 45 % dry-basis. During experiments, paddy samples collected before and after drying were determined for the moisture content and milling quality in terms of head yield and whiteness. Temperatures at various positions , as shown in Figure 2, were measured by type k thermocouple connected with a data logger with an accuracy of $\pm$ 1 °C. The quantity of diesel oil consumed was recorded as well. In case of a 2.5-5 ton/h capacity fluidized bed dryer, inlet air temperature was 150 °C, air flow rate was 2.57 m^3/s, corresponding to a superficial air velocity of 2.1 m/s. Initial moisture content of paddy was roughly 27 % dry-basis. Finally, experiments were made with a 5-10 ton/h capacity fluidized bed dryer using an air flow rate of 5.57 m^3/s, corresponding to a superficial air velocity of 2.2 m/s, a range of inlet air temperature from 115 °C to 130 °C and initial moisture content of paddy varied from 22 % to 30 % dry-basis.

In order to determine moisture content of paddy, samples were kept in a hot air oven at temperature of 103 °C for 72 hours. Milling quality was investigated and compared with the reference samples dried by ambient air. Head yield is defined as mass of head rice divided by mass of paddy. For the whiteness of rice kernels, it was measured with a Kett meter, model C-300. Lower value of reading means more yellow. The test method of paddy quality was made accordingly as the guidelines of Rice Research Institute, Ministry of Agriculture and Agricultural Co-Operatives, Thailand.

RESULTS AND DISCUSSION

To analyse the performance of prototype and commercial units, data collected from different testing time at steady-state operation, as shown in table 1, were employed.

From table 1, total energy consumption including electrical and thermal energy could be divided into 3 levels. Firstly, when paddy was dried from 44-46 % dry-basis to 24 % dry-basis using inlet air temperature of 104-120 °C and air recycled of 66 %, total energy consumption was approximately 1.64 MJ/kg -water evaporated. Secondly, in case of reducing moisture content from 26-30 % dry-basis to 21-23 % dry-basis using inlet air temperature of 120-150 °C and air recycled of 53-69 %, total energy consumption varied from 2.5 to 4 MJ/kg-water evaporated. Finally, as paddy was dried from 22 % dry-basis to 20 % dry-basis by using inlet air temperature of 115 °C and air recycled of 69 % , total energy consumption was approximately 8.6 MJ/kg-water evaporated.

As mentioned above, it reveals that the application of fluidized bed technology for grain drying at high moisture level is of great advantages. However, at low moisture level , normally lower than 24 % dry-basis, this technique is not very efficient. This can be simply explained that at low moisture level, moisture movement is limited mostly by moisture diffusion in grain kernels. Thus, better heat and mass transfer between grain and air obtained by fluidization technique can not play much role.

Paddy quality in terms of head yield and whiteness is shown in table 1. It is quite acceptable compared to paddy dried by ambient air. Though drying air temperature is very high, the quality is still maintained. This is due to very short residence time for it takes only a few minutes.

This study confirms the works reported by Soponronnarit and Prachayawarakorn (1994) and Sutherland and Ghaly (1990).

As of November 1996, more than 60 units of fluidized bed paddy dryer have been sold. The success of commercialization is due to : 1) Recycling of exhaust air which significantly reduces energy consumption, 2) Very high capacity due to possible use of very high drying air temperature and finally 3) Very close collaboration among our research team, a private manufacturer of drying equipment and a private user.

CONCLUSION

Field trial of the prototype fluidized bed paddy dryer with a capacity of 0.82 ton/h during the wet harvesting season in 1994 for totally 1,497 hours indicated that the unit was easy to use, efficiently performed in terms of very fast drying rate and low energy consumption and gave uniform product moisture content, compared to the two existing cross-flow columnar dryers installed at the same site, as reported by the owner of the paddy merchant site though there was no comparative performance figures.

The experimental results indicate that the prototype and commercial units operate efficiently and immensely reduce the moisture content of paddy especially at high moisture level. In reducing the moisture content from 44-46 % dry-basis to 24 % dry-basis using inlet air temperature of 104-120°C and air recycled of 66 %, total energy consumption is 1.64 MJ/kg-water evaporated. When paddy is dried from 26-30 % dry-basis to 21-23 % dry-basis using inlet air temperature of 120-150°C and air recycled of 53-69 %, it requires total energy consumption of 2.5 - 4 MJ/kg-water evaporated. But at the condition of paddy dried from 22 % dry-basis to 20 % dry-basis by using inlet air temperature of 115 °C and air recycled of 69 %, total energy consumption increases sharply to 8.6 MJ/kg-water evaporated. At the above conditions, the paddy quality after drying in terms of head yield and whiteness is maintained.

Since the beginning of 1996, more than 60 units with capacity of 5 tons/h and 10 tons/h have been commercialized in Thailand and exported (as of November 1996).

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The authors acknowledge Australian Centre for International Agricultural Research and The Thailand Research Fund for continuous financial support, and finally to Rice Research Institute for providing equipments for testing paddy quality.

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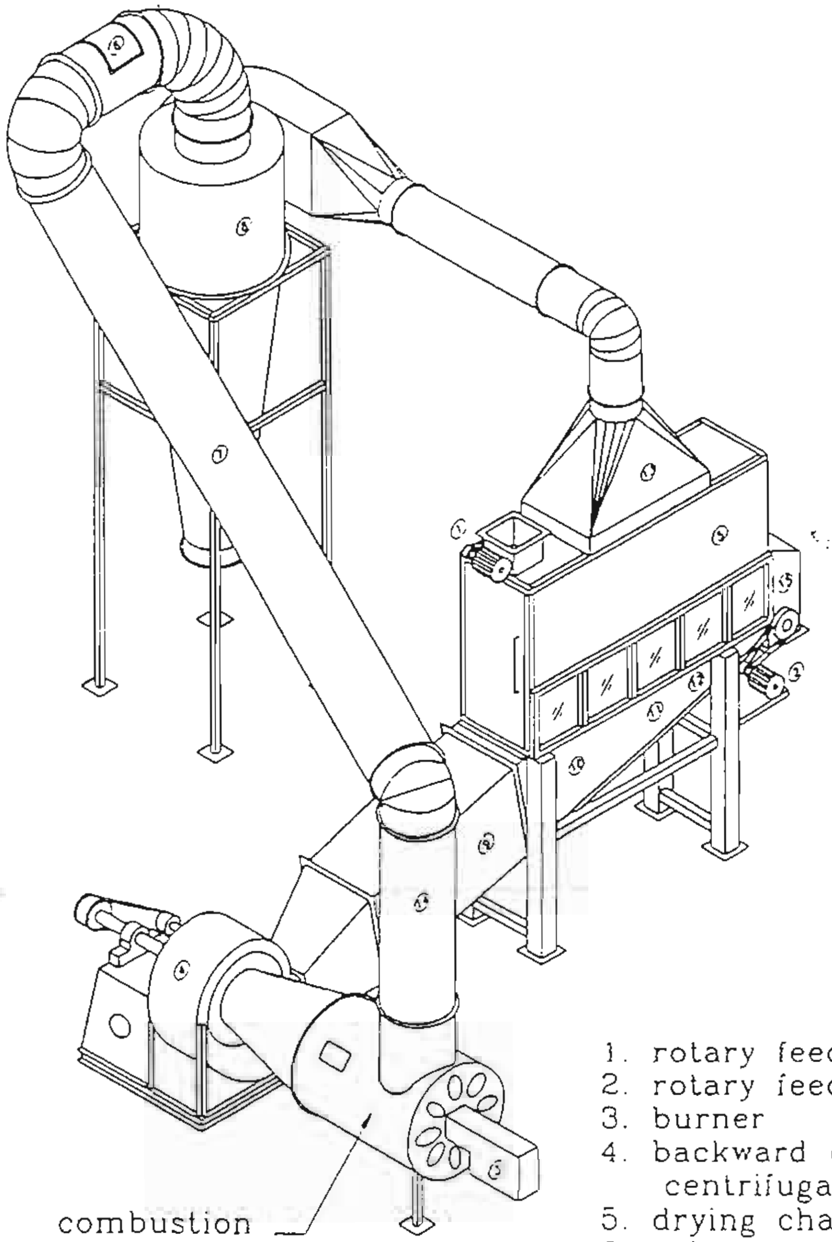
Table 1 Performance test results of commercial fluidized bed paddy dryer

Drying air temp. (°C)	Air recycled (%)	Inlet moisture of paddy (%db)	Outlet moisture of paddy (%db)	Outlet grain temp. (°C)	Electrical energy consumed ($MJ/kg\text{-}H_2O$)	Thermal energy consumed ($MJ/kg\text{-}H_2O$)	Head yield[d] (%)	Reference[e] head yield (%)	Whiteness[d]	Reference[e] whiteness	Testing hours	Drying capacity (ton/h)
60	66	27.0	23.2	47.0	0.83	3.41	30.1	35.4	-	-	1.0	1[a]
104	66	44.5	24.1	54.0	0.14	1.36	50.5	56.9	43.1	43.7	18.5	1[a]
106	66	45.3	24.2	55.0	0.14	1.29	50.5	56.9	43.1	43.7	6.0	1[a]
107	66	46.6	24.3	56.0	0.13	1.36	50.5	56.9	43.1	43.7	23.0	1[a]
108	66	44.6	24.0	56.0	0.13	1.49	50.5	56.9	43.1	43.7	1.0	1[a]
115	69	22.0	20.1	54.0	0.83	7.80	53.2	57.4	40.3	44.4	5.0	9.5[c]
116	69	26.0	22.5	52.0	0.43	3.13	54.3	57.2	40.7	44.2	35.0	9.5[c]
120	69	28.7	22.5	54.0	0.26	2.57	53.9	53.9	40.0	40.1	46.0	9.5[c]
120	66	45.1	24.6	58.0	0.14	1.98	50.5	56.2	43.1	43.7	1.0	1[a]
130	69	30.6	23.0	57.0	0.21	2.21	57.0	57.0	43.7	43.8	51.0	9.5[c]
150	53	27.0	21.0	63.0	0.15	3.90	48.1	56.2	36.8	42.6	29.0	4.8[b]

a Dryer with capacity of 1-2 tons/h, b Dryer with capacity of 2.5-5 tons/h, c Dryer with capacity of 5-10 tons/h

d Dried in fluidized bed dryer, e Dried by ambient air



1. rotary feeder
2. rotary feeder
3. burner
4. backward curved blade centrifugal fan
5. drying chamber
6. exhaust air
7. air recycled
8. cyclone

9–15. (positions of temperature measurement)

Figure 1 Fluidized bed dryer

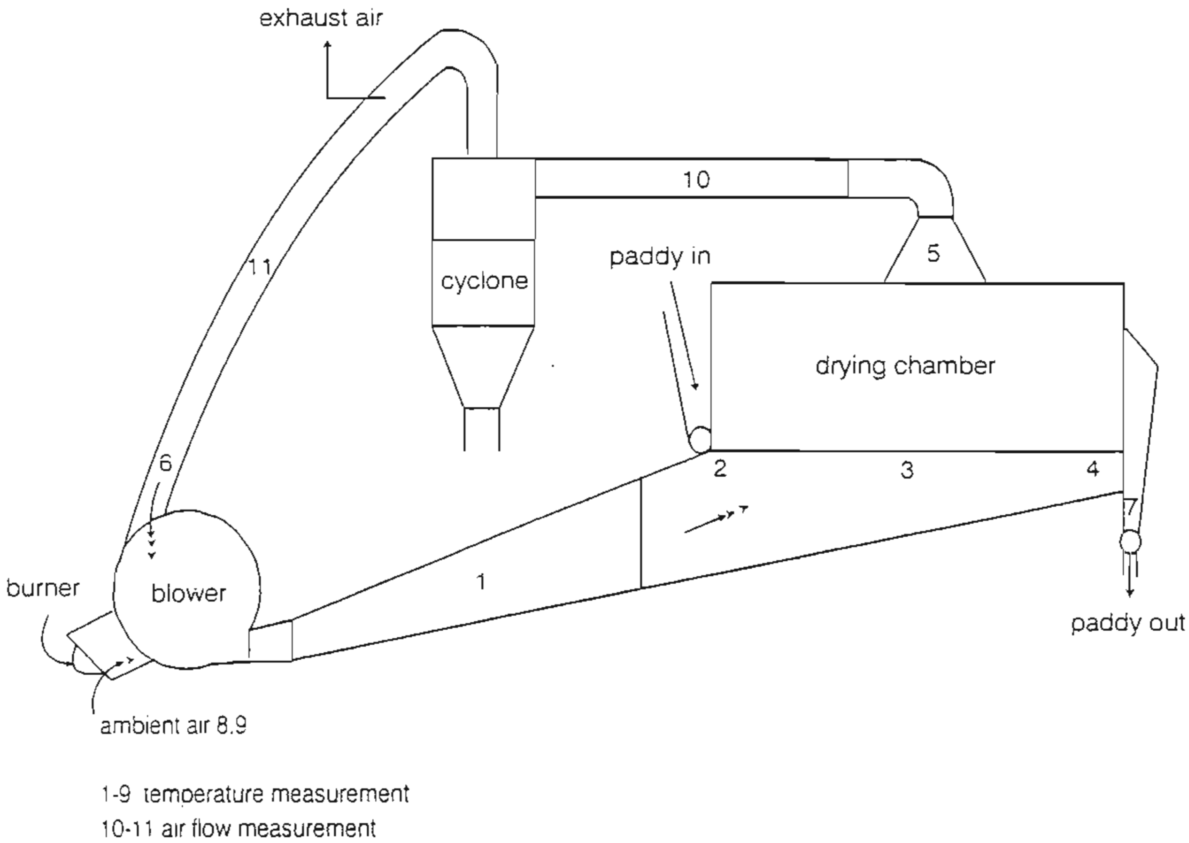


Figure 2 Diagram of fluidized bed paddy dryer

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Potential Evaluation of Fluidized Bed Corn Dryer

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ABSTRACT

The aim of this work was to investigate the drying characteristics of corn in a fluidized bed dryer and the performance of this dryer. The experiments were done with a fluidized bed dryer with capacity of 1.6-3 tons/h at conditions of 18-40 percent dry-basis initial moisture content of freshly harvested corn, 78-84 percent air recycled, 130 to 175°C inlet hot air temperature, 2.7 m/s superficial air velocity and 17 to 19 cm bed depths. The results revealed that thermal equilibrium between grain and drying air can be obtained until bed depth of 19 cm. The drying kinetics of corn kernels was found to be of the thin layer type. The theoretical drying equation could describe the results well. The results suggested that fluidized bed dryer should be applied only in corn drying at high moisture level. Thermal efficiency for corn drying at high moisture level was 36 to 50 percent depending on drying conditions. As to corn quality, the percentages of breakage and stress cracks of corn were still preserved when corn was dried from 18 to 23 percent dry-basis to 16 to 18 percent dry-basis using 130 to 175°C inlet hot air temperature.

INTRODUCTION

Drying commonly describes the thermal process from which heat is transferred from a fluid medium to the moist solid particles to remove the volatile substance within products. The methods of heat transfer can be divided into three mechanisms: conduction, convection and radiation. Normally in grain drying, heat is transferred by convection. Therefore, the most important thing is the contact between grain and drying air in order to transfer heat effectively. Many types of mechanical dryers for grain drying such as crossflow dryer (Gustafson *et al*,1981, Pierce and Thompson, 1981) and rotary dryer (Saeman and Mitchell, 1954), have been designed and investigated in terms of energy consumption and product quality. The fluidized bed dryer is a type of mechanical dryer which is widely used in industrial drying because of its several advantages when compared with the other types of dryer, such as:

1. There are no mechanical moving parts and therefore the maintenance cost is low.
2. Besause of high heat and mass transfer rates between fluidized particles and fluid medium, drying time is relatively short. Thus, the size of dryer is small but with high capability.
3. Rapid mixing of particles leads to nearly isothermal condition throughout a bed which makes control of the continuous dryer easy.

These advantages were obtained using high air velocity, approximately 1.5 times of superficial velocity at minimum fluidizing condition. By virtue of this, thermal efficiency, which is defined as the ratio of heat used for removing moisture within kernels to total energy input, is rather low with no air recirculation system. However, it is possible to improve it by installing air recirculation and/or increasing inlet hot air temperature (Giner and Demichelis, 1988). Hot air temperature can be further increased until grain temperature closes to that of deterioration in grain quality. Paddy dried at inlet air temperature higher than 150°C will become more intense yellow because of non-enzymatic browning reaction (Soponronnarit and Prachayawarakorn, 1994). In case of corn drying, it was found that stress cracks in the corn kernels increased with the increase of inlet air temperature (Srivastava *et al*, 1974) and breakage susceptibilities became greater with the increase of drying rate (Gunasekaran and Paulsen, 1985). In contrast with that mentioned earlier, when using high humidity drying of corn, stress cracks and breakage susceptibilities were reduced (Estrada and Litchfield, 1993). Thompson and Foster (1963) investigated the effect of drying air temperature on stress cracks and breakage susceptibilities and found that the stress crack in the corn kernels was a major factor that affected high breakage susceptibility. Herum and Blaisdell (1981) studied the effects of breakage susceptibilities. The results showed that the breakage susceptibilities increased rapidly as moisture content of corn was reduced from 14 percent wet-basis to 12 percent wet-basis and slightly reduced at grain temperature of 4-38°C.

In 1995, a fluidized bed paddy dryer with capacity of 10 tons/h was commercialized and approximately 48 units were sold. The potential for corn drying by fluidization technique seems to have been proven. The fluidized bed paddy dryer was, therefore, modified for corn drying.

The objective of this research was to investigate the drying characteristics of corn in fluidized dryer and the performance of this dryer as well.

MATERIALS AND METHODS

The fluidized bed dryer with 1.6 to 3 tons/h capacity (Figure 1) comprises principally a drying chamber with dimension of 0.7 x 2.1 x 1.3 m, a diesel oil burner, a cyclone separator and a backward curved blade centrifugal fan driven by a 25-hp motor. The feed rate of corn fed in and out is controlled by rotary feeders and bed depth of corn is controlled by a weir. Corn moves in perpendicular direction with the flowing hot air of which temperature is controlled by a thermostat with accuracy of ±3°C. In order to collect large impurities, exhaust air is flowed through the cyclone separator. Then a small part of exhaust air is delivered to the atmosphere and the rest is recycled, mixed together with the fresh air and then reheated to a desired temperature in the combustion chamber. In this work, inlet hot air temperature varied between 130°C and 175°C, air flow rate was fixed at 3.39 m^3/s corresponding to 2.7 m/s superficial air velocity (1.5 times of minimum fluidized bed velocity), fraction of air recycled varied between 0.78 and 0.84 depending on initial moisture content of corn, and bed depth of corn varied between 17 cm and 22 cm. Residence time varied between 3 and 7 minutes depending on feed rate and bed depth of corn. When the system was adapted to steady-state condition, temperatures at various positions measured with K-type thermocouples were transfered to a data logger (accuracy of ±1°C) as shown in Figure 1, and the amount of oil consumed was recorded as well. For grain temperature, corn kernels exiting from the dryer were put into an insulation container and measured by a thermometer. In addition, the moisture content and quality in terms of breakage and stress cracks were determined.

To determine the moisture content of corn, the samples were placed in a hot air oven at a fixed temperature of 103°C for 72 hrs.

The percentage of stress cracks which is defined as the ratio of weight of stress cracked corn to total weight, was determined by the inspection of 150 g of corn kernels per sample. A wooden box with a fluorescent lamp was used to inspect each corn kernel. The percentage of breakage was defined as the ratio of weight of broken corn to total weight.

RESULTS AND DISCUSSION

Drying

In the continuous dryer design, moisture distribution exiting from the dryer has to be considered because it affects the corn quality or revenue, i.e., mycotoxins are easily produced by microorganisms due to high moisture content of corn, especially moisture content higher than 18 to 19 percent wet-basis (Kositcharoenkul *et al*,1992), or it loses the weight due to excess drying that results in lower income. As shown in Figure 2, inlet moisture content of corn did not vary much during the experiment. However, since the time when corn kernels move in the drying chamber, at the later operation period was shorter than that at former operation period, the outlet moisture content of corn at the later operation period was slightly higher as compared to that at the former operation period.

Heat transfer rate in fluidized bed dryer is rather high because of high air velocity and the contact between particles and drying air is relatively effective. Consequently, the temperature of the grain as it enters the drying chamber developed rapidly and is close to temperature equilibrium between grain and drying air as shown in Figure 3, and the result at depth of 19 cm was the same as in Figure 3. Then, only one drying equation can describe the moisture transfer of grain fully exposed to a constant drying air condition. In general, the mechanism of moisture transfer in grain is controlled by internal diffusion although the surface of the grain is rather wet at moisture levels of 28 to 38 percent dry-basis (Satayaprasert and Vanishsriwatana, 1992, and Soponronnarit and Prachayawarakorn, 1994). Therefore, the theoretical drying equation that depicted the moisture movement in grain are:

(1) $$\frac{M(\tau)-M_{eq}}{M_{in}-M_{eq}}=\frac{6}{p^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[\frac{-n^2p^2\tau D}{R^2}\right]$$

and

(2) $$D=0.14230\exp\left(\frac{-4496.2}{t_s+273}\right)$$

Where	$M(t)$	=	average moisture content at t time, dry-basis
	M_{eq}	=	equilibrium moisture content , dry-basis
	D	=	effective diffusion coefficient, m^2/h
	R	=	radius sphere of corn (R = 0.004 m for corn), m
	t	=	drying time, h
	t_s	=	grain temperature, °C

The solution of equation (1) must satisfy assumptions, i.e., sphere-shaped corn kernels, surface moisture content equilibrium between grain surface and drying air as well as constant grain temperature during a drying condition. The equation of effective diffusion coefficient (2) was developed by Phudphong et al (1990). In his work, only three terms in equation (1) was enough to explain the results. As shown in Figure 4, it was found that final moisture content predicted from equation (1) was in accordance with the experimental results.

Thermal Efficiency

Figure 5 shows that thermal efficiency increased with the increase of inlet hot air temperature at 28 to 40 percent (dry basis) initial moisture content. But when initial moisture content of corn was in the range of 18 to 23 percent (dry basis), thermal efficiency was lower than the above case, and also slightly reduced with the increase of inlet hot air temperature as shown in Figure 5. The experimental results suggest that a fluidized bed dryer could be applied to corn drying at high moisture level.

Corn Quality

Figure 6 shows that the percentage of stress cracked kernel at low drying rate slightly increased as compared to the reference sample, and drying rate did not significantly affect stress cracked kernel. However, when drying rate was further increased, the percentage of stress cracked kernel rapidly increased because the kernel surface became more rigid. For percentage of broken kernel dried at the same condition as in Figure 6, it was found that the percentage of broken kernel after drying was insignificantly different from the reference sample. These results also confirmed the fact that high or low percentage of broken kernel does not necessarily correspond to high or low percentage of stress cracked kernel (Paulsen *et al*, 1983), as shown in Table 1.

CONCLUSION

From the experimental results of corn drying in a fluidized bed dryer, it could be concluded that:

1. During drying conditions at 18 to 38 percent dry-basis, 130 to 175°C inlet hot air temperature and 2.7 m/s superficial air velocity, the maximum bed depth of corn in which outlet grain temperature was nearly equal to exhaust air temperature was 19 cm. A theoretical drying equation in which corn kernels was assumed to be sphere-shaped explained the moisture transfer in grain.
2. The fluidized bed dryer should be taken into account for corn drying at high moisture level. When corn was dried from 28 to 40 percent (dry basis) to 19 to 31 percent (dry basis) using 2.7 m/s superficial air velocity, 130 to 160°C inlet hot air temperature, 78 percent air recycled, 17 and 19 cm bed depths, and 3 to 5 minute residence time, thermal efficiency varied between 36 and 50 percent depending on drying conditions.
3. With respect to corn quality, during the experiment at conditions of 18 to 23 percent (dry basis) down to 16 to 18 percent (dry basis) using 130 to 175°C inlet hot air temperature, the percentages of breakage and stress cracks of corn were still maintained as compared to the reference sample.

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Table 1. Testing of corn quality

Drying hot air temp. (°C)	Air recycled	Inlet moisture content (%db)	Outlet moisture content (%db)	Outlet grain temp. (°C)	Breakage		Stress cracks		Testing hours	Capacity (tons/h)
					Dried in fluidized bed (wt%)	Reference (wt%)	Dried in fluidized bed (wt%)	Reference (wt%)		
130[a]	84	22.2	19.12	68.3	1.91	1.04	0.59	0.19	2	1.5
130[a]	78	38.23	30.79	68.1	-	-	-	-	6	2.0
140[b]	78	32.72	27.21	74.3	-	-	-	-	10	3.0
150[c]	78	28.19	19.20	-	-	-	-	-	7	2.0
150[a]	34	18.56	16.73	74.0	1.31	1.72	1.03	0.59	2	1.5
160[a]	78	40.32	26.32	-	-	-	-	-	4	1.8
170[c]	64	21.14	14.16	97.4	2.82	2.44	32.69	0.62	5	1.6
175[a]	84	22.77	18.18	95.9	1.54	1.55	3.34	0.79	7	1.8

a 17 cm Bed depth, b 19 cm Bed depth, c 22 cm Bed depth

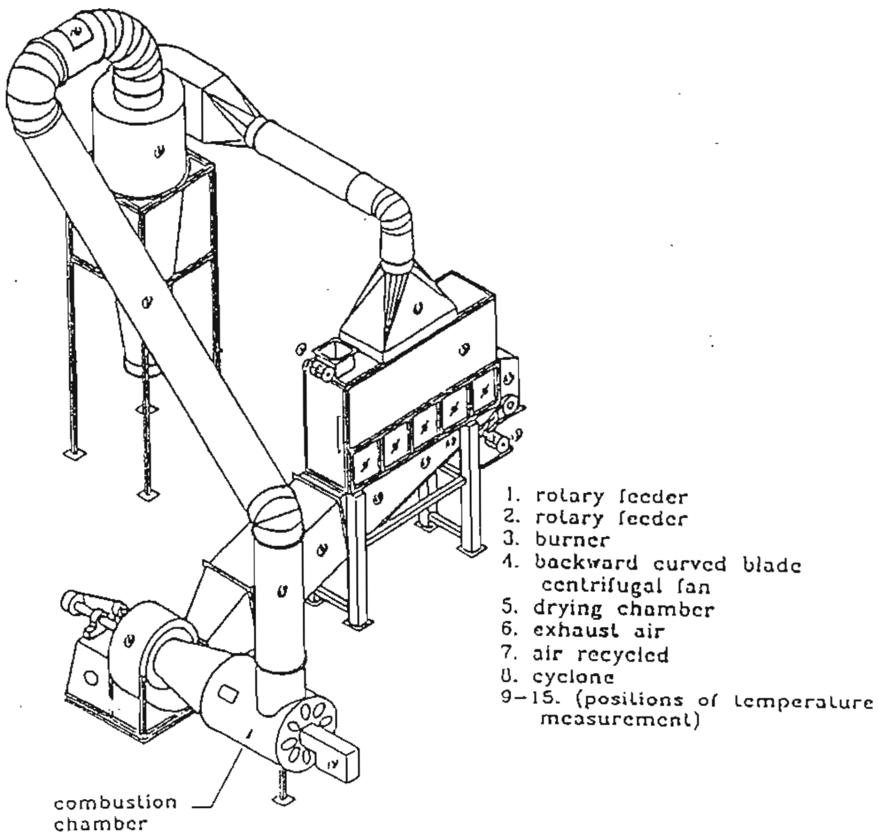

Figure 1. Fluidized bed dryer

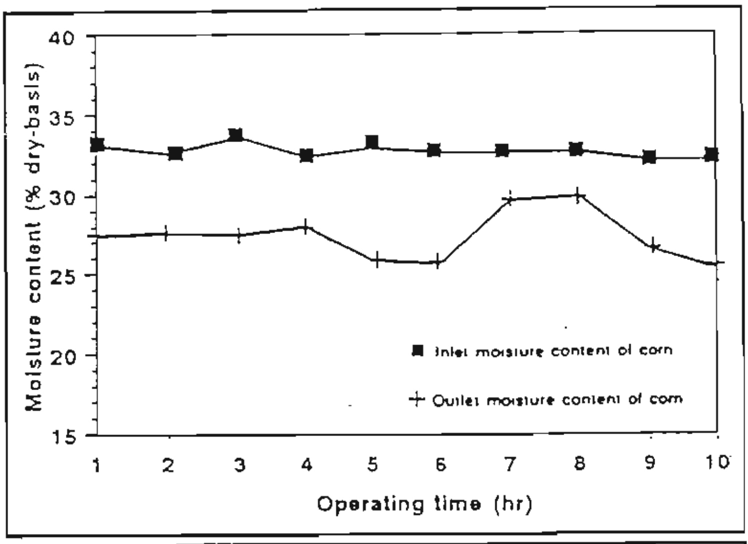

Figure 2. Evolution of moisture content of corn (Inlet hot air temperature=140°C, Bed depth=17 cm) (Superficial air velocity=2.7m/s)

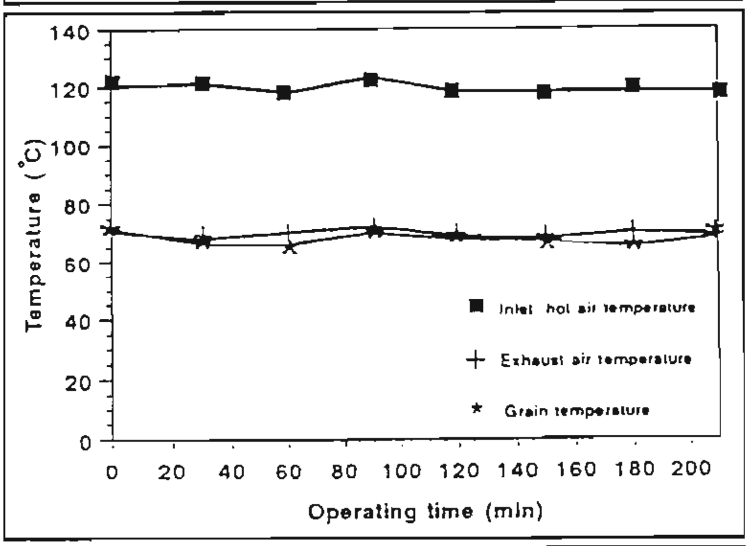

Figure 3. Evolution of temperatures (Bed depth=17 cm, Superficial air velocity-2.7m/s) (Initial moisture content=22.2 % dry-basis)

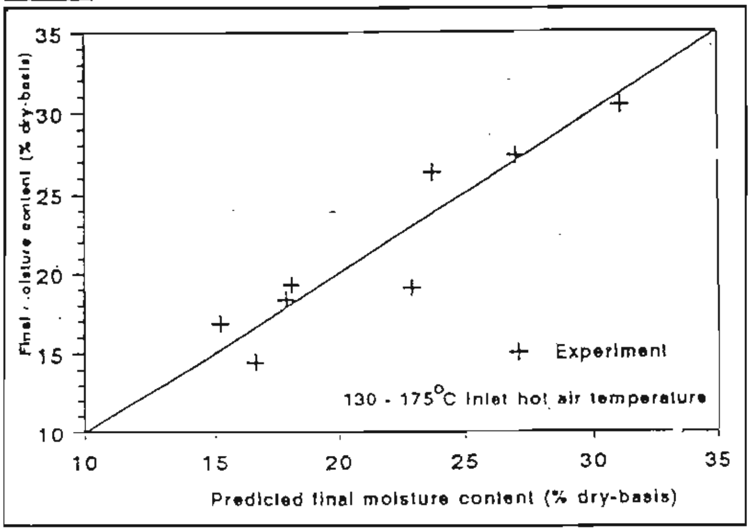

Figure 4. Comparison of final moisture content between Phudpong's diffusion model and experiment (18-40 % dry-basis initial moisture content.

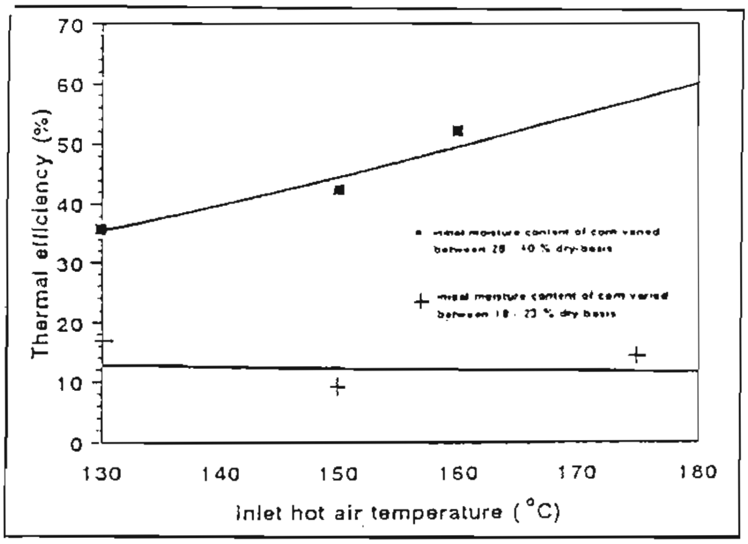

Figure 5. Effect of inlet hot air temperature on thermal efficiency (Bed depth=17 cm, Superficial air velocity-2.7 m/s)

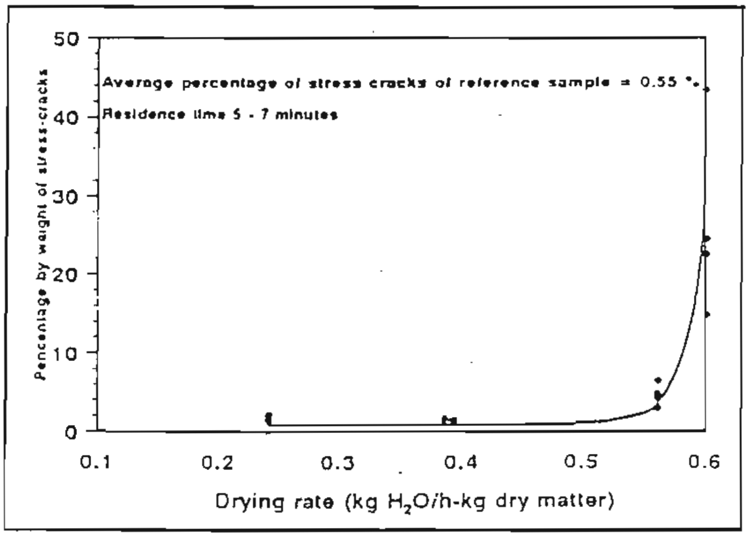

Figure 6. Effect of drying rate on stress-cracks (Inlet hot air temperature varied between 130-175°C) (Initial moisture content varied between 18-23 % dry-basis)

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Delay of Deterioration of Wet Paddy By Ventilation

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ABSTRACT

The objective of this research was to study the delay of deterioration of wet paddy by ventilation with cool air (15+8°C) and ambient air (30±8°C), continuous and intermittent basis. Initial moisture content of paddy was 21.0, 22.2 and 26.0 percent wet-basis. Air flow rate was 0.35 m^3/ min-m^3 of paddy. Paddy could be cooled down to 20°C and to near ambient air temperature within one day by cool air and ambient air ventilation respectively. The quality of paddy could be maintained at acceptable levels for more than one month, either cool air ventilation or ambient air ventilation. The quality of paddy in terms of whiteness was better for paddy ventilated with cool air.

INTRODUCTION

Harvested paddy normally with moisture content of 18.0 to26.0 percent wet basis can be easily damaged by fungi. Heat from its respiration also decreases its quality. To avoid these effects the paddy must be dried to moisture content of 12.0 to14.0 percent wet basis, the level that is appropriate for milling and storage. Recently, grain dryers are widely used for improving the efficiency of drying process although their drying capacity is not enough during the paddy season. As a result, paddy stocks await drying in the mill and are damaged by fungi and heat from respiration.

Phillips *et al* (1988) studied the yellowing of paddy during in-store drying. Experimenting with initial paddy moisture content of 22.0 percent wet basis and specific air flow rate of 1.5 m^3/ min-ton of paddy, he found that it requires eight more weeks to decrease the moisture content to 14 percent wet basis. Yellowing appeared clearly after the fifth week and increased to 4.5 to 5.5 percent after 365 days. Fungi such as *Aspergillus, Penicillium and Rhizopus* were also found in the paddy mound. The relationship between yellowing and fungi growth was not established in this study.

Phillips *et al* (1989) studied the yellowing of paddy during drying. The experiments included four conditions:

1. Pile the moist paddy up in open-air and in a bin.
2. Store the moist paddy in sacks and leave in open-air and in a bin.
3. Pile the dry paddy up in open-air and in a bin.
4. Store the dry paddy in sacks and leave in open-air and in a bin.

The initial moisture content of paddy was more than 20.0 percent wet basis and ambient relative humidity was in the range of 44 to 84 percent. Through ocular inspection, extreme fungi infection was observed in two days and 100 percent yellowing was observed in five days in the first and second conditions. The temperature in the middle of the paddy mound in these cases was up to 65°C after 6 days. In the fourth condition, paddy temperature and yellowing were down to 40°C and 1 to 3 percent respectively after 30 days. Comparing the yellowing under the four conditions, the second one had the most yellowing, followed by the first, the fourth and third respectively.

Maier *et al* (1993) studied continuous and intermittent ventilation of paddy by cooled and ambient air using a mathematical model to predict the change in paddy temperature and moisture content. In the model, paddy was contained in a silo with diameter of 15 m and height of 10 m. Initial moisture content and specific air flow rate were 13 percent (wet basis) and in the range of 0.05 to 0.5 m^3/min-ton of paddy respectively. The study showed that continuous ventilation of cooled air decreased paddy temperature down to 15°C in 110 to 144 hr and decreased moisture content slightly. Continuous ventilation with ambient air could not decrease paddy temperature down to 25°C either in summer or the rainy season (ambient air data of the middle area of Thailand in 1988-1989). Intermittent ventilation with ambient relative humidity control (ventilate when RH is less than 75%), paddy temperature was more than 26°C, moisture content decreased 0.8 percent from its initial moisture content and energy consumption was 38 to 64 percent lower than the continuous ventilation.

Baso *et al.* (1989) studied the effect of water activity and air components (O_2, CO_2) on the yellowing of paddy and found that temperature and water activity affected the yellowing, O_2 had a slight effect, and CO_2 did not.

Thanh (1995) studied the deterioration of wet paddy with initial moisture content of 20 to 29 percent (wet basis) ventilated by air flow rate of 1.8 m^3/min-m^3 of paddy. The results showed that paddy with moisture content of 20 percent, 24 percent and 29 percent (wet basis) could be stored for 15, 6 to 7 and 4 to 6 days respectively in the intermittent ventilation of 49 to 50 hours.

From the previous researches, paddy quality while in storage depends on several factors such as initial moisture content and temperature of paddy and deterioration of fungi infection. Storage period can be extended by using air ventilation. In order to maintain paddy quality, the objective of this research is to study the delay of deterioration of wet paddy by ventilation with cooled air and ambient air.

MATERIALS AND METHODS

Experimental paddy bins as shown in Figure 1 consisted of a paddy bin with diameter of 57 cm, height of 86 cm and cover at the top. Perforated sheet with ventilated area of 35.6 percent was installed at the level of 20 cm above the bottom of the bin. Fiber glass insulator with 2 inches thickness was used to insulate the bin and also air tube in case of cooled air ventilation. The cooled air ventilation system consisted of a 946 watt compressor, 44 watt condenser fan and evaporator fan. Ambient air ventilation system consisted of a 88 watt centrifugal fan.

Experiments were performed by containing 80 kg of paddy with initial moisture content of 21percent, 22.2 percent and 26.0 percent (wet basis) in the bins and ventilating with cooled and ambient air. Continuous ventilation was used in the case of the initial moisture content of 22.0 and 26.0 percent (wet basis) while in case of 21 percent (wet basis), intermittent ventilation (9.00am-5.00pm) was used instead. Air conditions used in the experiment were cooled air temperature of 15+8°C, ambient air temperature of 30±8°C, and specific air flow rate of 0.35 m^3/min-m^3 of paddy. Paddy temperature at each 17 cm high interval, wet bulb and dry bulb temperature and inlet air temperature of the bins were measured by thermocouple type K connected with data logger with accuracy of ±1 °C.

During the experiments, paddy samples were taken to test head yield and whiteness quality with Satake Miller and McGill Miller No.2. Whiteness and moisture content of paddy were measured by Kett Whiteness Meter model C-300 and oven method (100°C, 72-96 hr) respectively. Moisture content of paddy sample must be decreased to 14 percent (wet basis) immediately before testing.

RESULTS AND DISCUSSION

Temperature change in paddy mound

Experimental results showed that the average temperature in paddy mounds was decreased to 20°C and nearly ambient temperature in one day in case of continuous cooled and ambient ventilation respectively as shown in Figures 2 and 3. For intermittent ventilation as shown in Figure 4, the average temperature was 15 to 25°C and 25 to33°C in the case of cooled and ambient air ventilation respectively. The temperature of the mound increased when ventilation was stopped because of heat from respiration effect and heat transfer between each layer caused the difference in paddy temperature between each layer.

Moisture change in paddy mound

From the experiments, both ventilation could not only decrease paddy temperature but moisture content as well as shown in Table 1.

Table 1. Decrease of paddy moisture content of different 34 days-ventilation methods.

Air	Ventilation Method	Initial Moisture Content (%wb)	Final Moisture Content (%wb)
Cool	Continuous	22.2	14.2
	26.0	14.4	
Ambient	Continuous	22.2	18.0
	26.0	15.3	
Cool	Intermittent(daytime)	21.0	15.0
Ambient	Intermittent(daytime)	21.0	18.1

The difference in moisture content between each layer was due to mass transfer from the bottom layer. However, the moisture content at the top decreased faster than the other layers because of the mass transfer between paddy in ambient air (Figures 5-7).

Paddy quality after milling

Experimental results of paddy head yield and whiteness after milling are shown in Figures 8-13 and Table 2.

Table 2. Paddy whiteness of different ventilation methods.

Air	Ventilation Method	Duration (days)	Initial Moisture Content (%w.b.)	Initial Whiteness	Whiteness Decrease	
					Minimum	%
Cool	Continuous	56	22.2	39.0	36.4	7.8
		49	26.0	45.0	41.4	11.0
Ambient	Continuous	56	22.2	39.0	35.4	10.4
		49	26.0	45.0	36.7	21.1
Cool	Intermittent (daytime)	34	21.0	45.6	41.4	9.2
Ambient	Intermittent (daytime)	34	21.0	45.6	39.0	14.4

Considering storage duration and acceptable whiteness at the level of 35, the results showed that both ventilation systems could extend the storage time without affecting whiteness and head yield of paddy under both systems were nearly the same. It could not be concluded that air ventilation affected paddy quality in case of increasing head yield.

The growth of fungi In paddy mound

Inspection of the growth of fungi in paddy mound in both ventilation systems revealed that the most appearent fungi were *Curvalaria tunata, Fusarium monilifome, Trichoconis padwickii* and *Drechslera oryzae*. Most fungi were found at the top of the mound. The amount of fungi in case of continuous cooled air ventilation was less than the continuous ambient one. The results also showed that paddy whiteness was not a function of fungi growth .

Energy consumption

The ventilation system used in the experiments gave more air flow rate than the desired flow rate in both ventilation systems. Thus, the actual energy consumption of the continuous cooled air ventilation which consumed electric power of 1034 W was 22.8 W or 2.2 percent, and the actual energy consumption of the continuous ambient air ventilation which consumed electic power of 88 W was 1.32 W or 1.5 percent. The results of energy consumption are shown in Table 3.

Table 3. Energy consumption of different 34 days-ventilation methods.

Ventilation Method	Initial Moisture Content	Final Moisture Content	Cost (Bah/m^3 of paddy)	Cost (Bah/kg of water
Continuous with cool air	22.2	14.2	236.1	4.00
	26.0	14.4	236.1	2.80
Continuous with ambient air	22.2	18.0	13.7	0.35
	26.0	15.3	13.7	0.18
Intermittent(daytime) with cool air	21.0	15.0	78.7	1.81
Intermittent(daytime) with ambient air	21.0	18.1	4.6	0.21

Remark: *Electricity price 1.65 baht/kW-h*

Comparing energy consumption between continuous and intermittent ventilation systems, it was found that intermittent ventilation with cooled air could save 66.7 percent energy cost while the one with ambient air could save 66.4 percent.

CONCLUSION

From the experimental results and discussions, it can be concluded that:

1. Continuous cooled and ambient air ventilation can decrease paddy temperature in a paddy mound down to 20°C and near ambient temperature respectively, while intermitent cooled and ambient air ventilation can decrease paddy temperature in the mound down to the range of 15 to 25°C and 25 to 33°C respectively. Both ventilation systems can also decrease paddy moisture content
2. Both ventilation systems can extend the storage time of wet paddy (21.0-26.0%, wet basis) to more than 1 month without affecting paddy whiteness.
3. Paddy whiteness from cooled air ventilation was better than the one from ambient air ventilation.

4. During the 34-day storage period, the energy costs of continuous cooled and ambient air ventilation were 236.1 and 13.7 baht/m^3 of paddy respectively. Intermittent ventilation with cooled and ambient air can save energy cost up to 6.7 percent and 66.4% respectively compared with continuous ventilation.

ACKNOWLEDGEMENT

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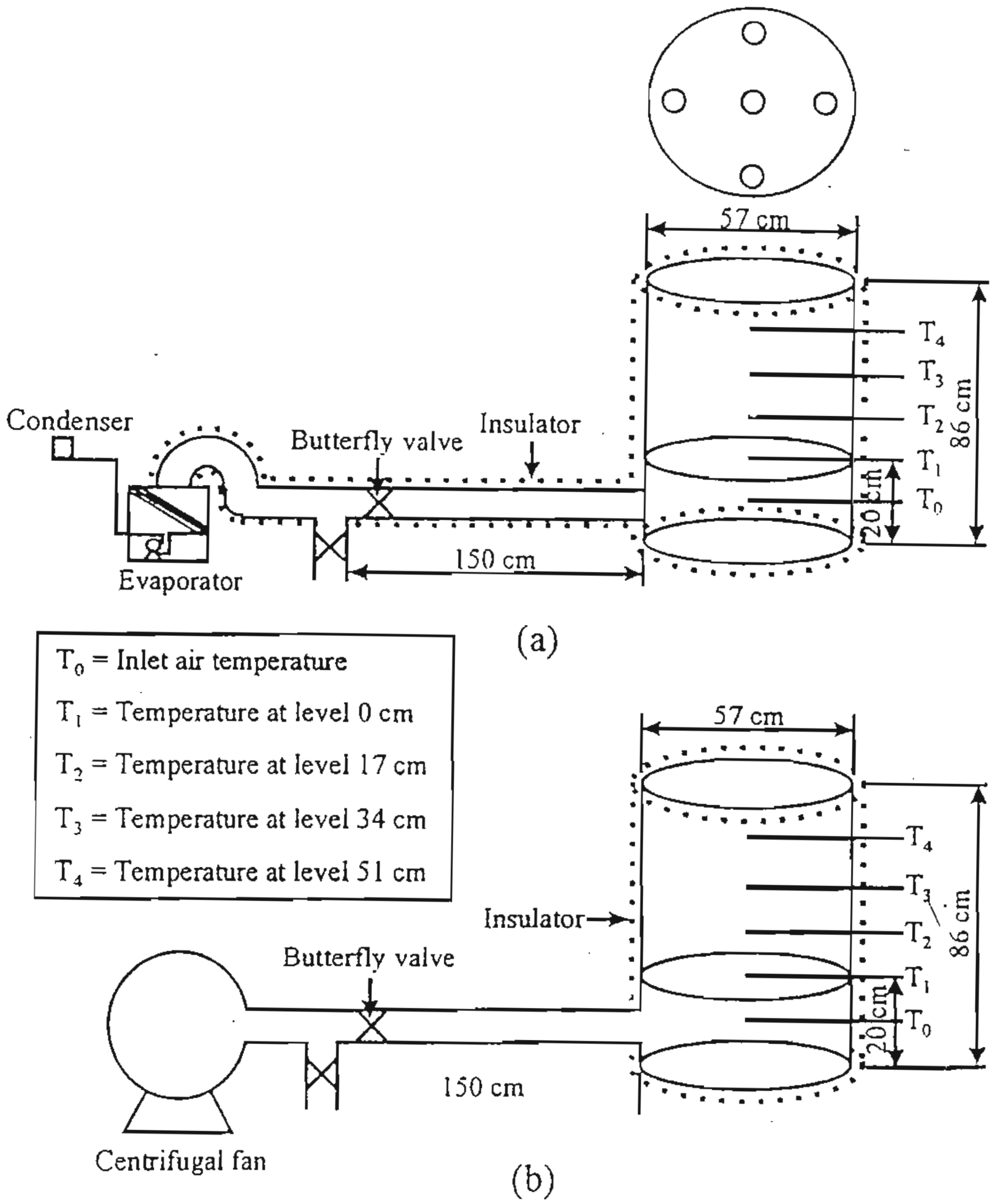
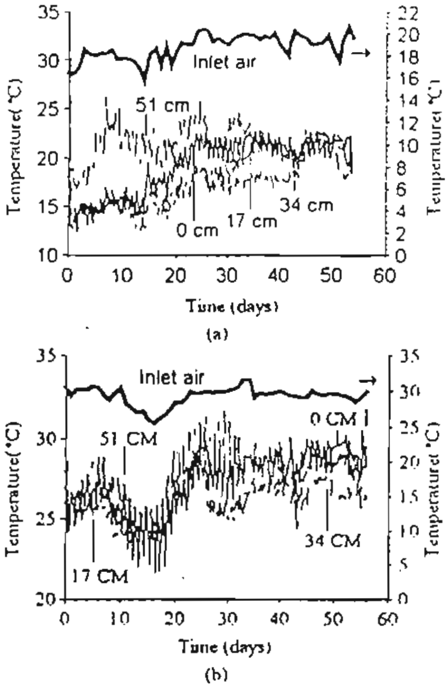
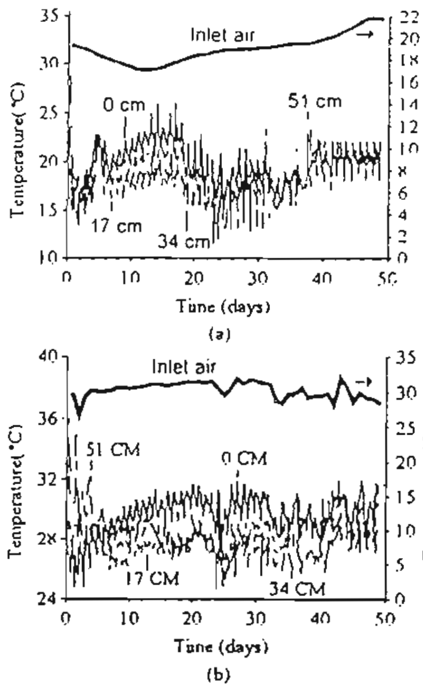


Figure 1 Experimental paddy bins
a. ventilated by cool air
b. ventilated by ambient air

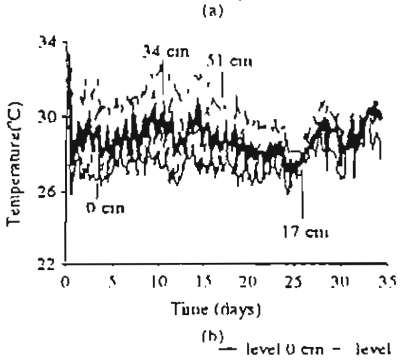


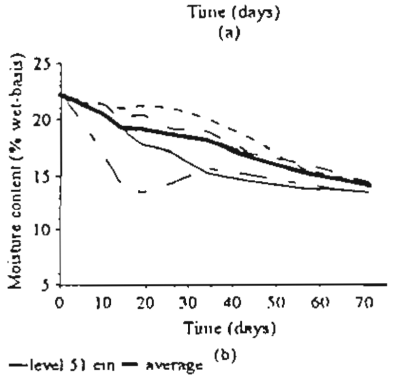


— level 0 cm - level 17 cm — level 34 cm —level 51 cm — average

Figure 1 Temperature at different levels in paddy bed
(initial moisture 22.2%w.b., flow rate 0.35 m^3/min-m^3 of paddy
a. ventilated continuously by cool air
b. ventilated continuously by ambient air

Figure 3 Temperature at different levels in paddy bed
(initial moisture 26.0%w.b., flow rate 0.35 m^3/min-m^3 of paddy
a. ventilated continuously by cool air
b. ventilated continuously by ambient air

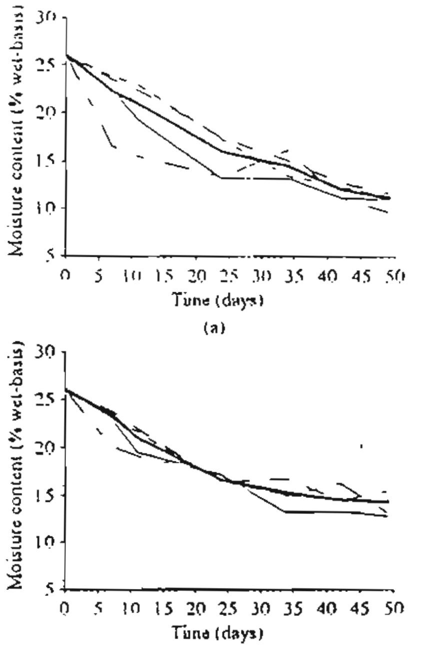


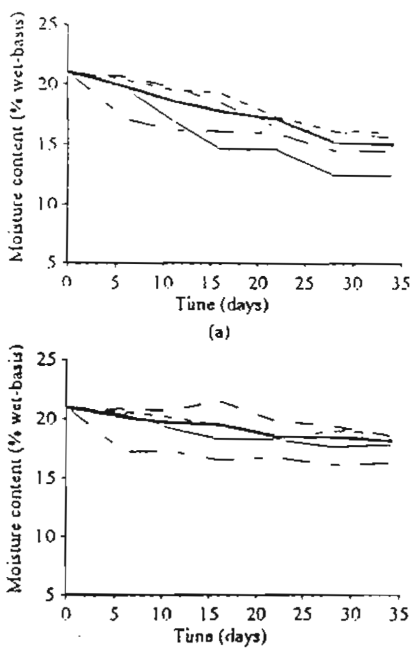


— level 0 cm - level 17 cm —level 34 cm —level 51 cm — average

Figure 4 Temperature at different levels in paddy bed
(initial moisture 21.0%w.b., flow rate 0.35 m^3/min-m^3 of paddy)
a. ventilated by cool air (9.00 am. to 5.00 pm.)
b. ventilated by ambient air (9.00 am. to 5.00pm.)

Figure 5 Moisture content at different levels in paddy bed
(initial moisture 22.2%w.b., flow rate 0.35 m^3/min-m^3 of paddy)
a. ventilated continuously by cool air
b. ventilated continuously by ambient air

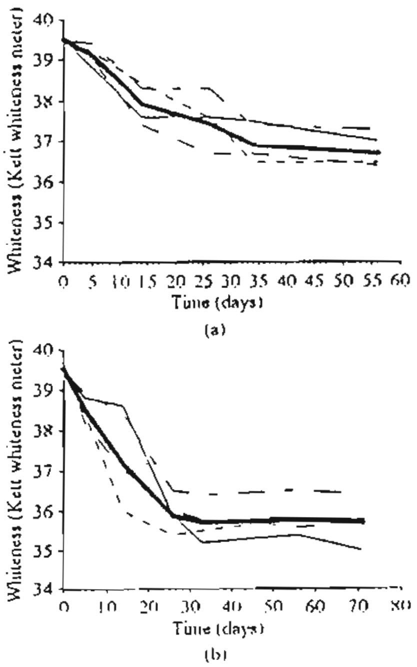


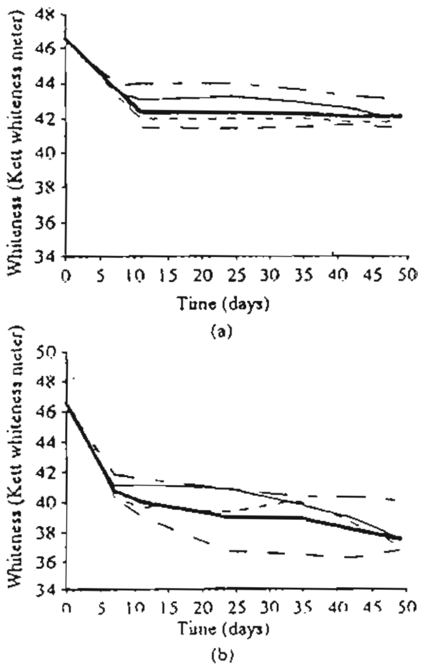


— level 0 cm - -level 17 cm — level 34 cm —level 51 cm — average

Figure 6 Moisture content at different levels in paddy bed
(initial moisture 26.0%w.b., flow rate 0.35 m^3/min-m^3 of paddy)
a. ventilated continuously by cool air
b. ventilated continuously by ambient air

Figure 7 Moisture content at different levels in paddy bed
(initial moisture 21.0%w.b., flow rate 0.35 m^3/min-m^3 of paddy)
a. ventilated by cool air (9.00 am. to 5.00 pm.)
b. ventilated by ambient air (9.00 am. to 5.00 pm.)

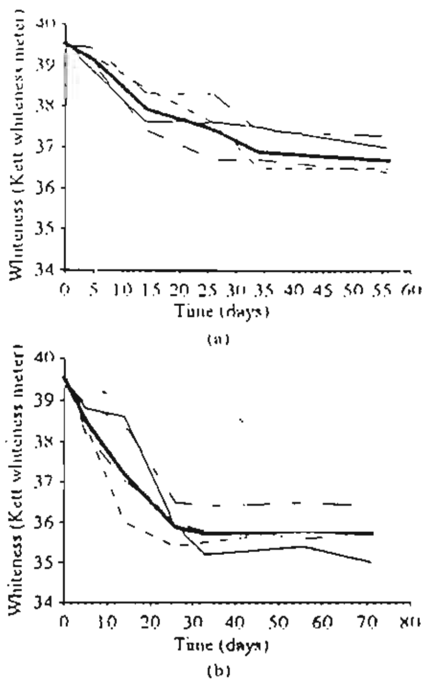


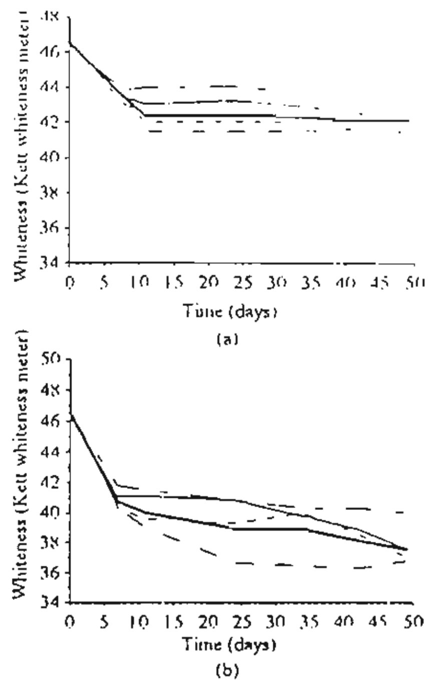


— level 0 cm - -level 17 cm — level 34 cm —level 51 cm — average

Figure 8 Whiteness at different levels in paddy bed
(initial moisture 22.2%w.b., flow rate 0.35 m^3/min-m^3 of paddy)
a. ventilated continuously by cool air
b. ventilated continuously by ambient air

Figure 9 Whiteness at different levels in paddy bed
(initial moisture 26.0%w.b., flow rate 0.35 m^3/min-m^3 of paddy)
a. ventilated continuously by cool air
b. ventilated continuously by ambient air

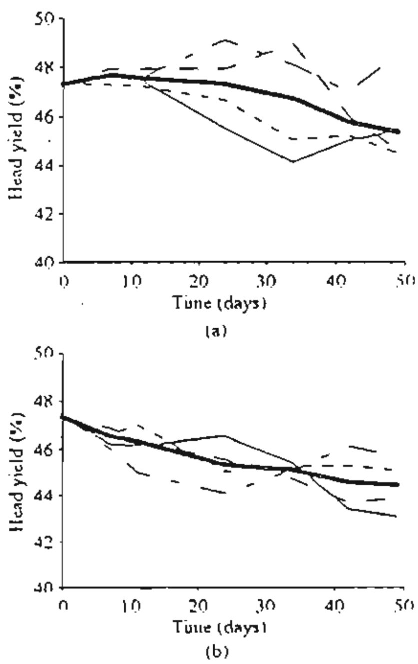


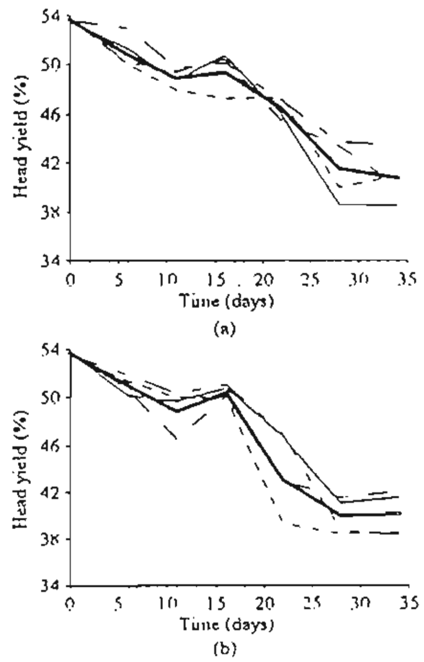


— level 0 cm - · level 17 cm — level 34 cm —level 51 cm ▬ average

Figure 8 Whiteness at different levels in paddy bed
(initial moisture 22.2%w.b., flow rate 0.35 m^3/min-m^3 of paddy)
a. ventilated continuously by cool air
b. ventilated continuously by ambient air

Figure 9 Whiteness at different levels in paddy bed
(initial moisture 26.0%w.b., flow rate 0.35 m^3/min-m^3 of paddy)
a. ventilated continuously by cool air
b. ventilated continuously by ambient air





— level 0 cm - · level 17 cm — level 34 cm —level 51 cm ▬ ~verage

Figure 12 Head yield at different levels in paddy bed
(initial moisture 26.0%w.b., flow rate 0.35 m^3/min-m^3 of paddy)
a. ventilated continuously by cool air
b. ventilated continuously by ambient air

Figure 13 Head yield at different levels in paddy bed
(initial moisture 21.0%w.b., flow rate 0.35 m^3/min-m^3 of paddy)
a. ventilated by cool air (9 am. to 5 pm.)
b. ventilated by ambient air (9 am. to 5 pm.)

PROCEEDINGS
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Mathematical Model for Industrial Scale Fluidized Bed Paddy Dryer

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ABSTRACT

The industrial scale continuous cross flow fluidized bed dryer (capacity 5-10 tons/hr) was studied and developed by using mathematical simulation and experimental results. The mathematical model was developed by modifying an existing model and was used to simulate for result prediction. The results determined for use in this study were moisture content and energy consumption data. Comparison of both simulation and experimental results was conducted. The case of study was divided into two cases: high and low initial moisture content of paddy case studies.

In case of low initial moisture content (21-26 of high initial moisture content (³ 26% db), predicted data of moisture content and energy consumption were little more than % db), predicted data of both moisture content and energy consumption were slightly less than experimental data. From the results of both case studies, it can be concluded that the agreement of data obtained from mathematical model simulation and experiment is fairly good.

INTRODUCTION

At present, fluidized bed drying technology for grain is becoming popular in Thailand. Its advantages over other drying technologies are: 1) uniform product moisture content; 2) no problem within the weather conditions; 3) use of much smaller drying chamber which translates to much lower initial cost; and 4) higher drying capacity compared with fixed bed or other types of continuous dryer because the quantity of air used in drying per unit mass of product is higher.

The main parameters which affect the rate of drying, product quality and energy consumption are temperature, specific air flow rate (ratio of inlet air flow rate to mass of dry paddy), quantity of air recycle etc. In this study, the methodology for determining the appropriate drying operations is a computer program mathematical simulation. It is less expensive for study compared with the experimental method.

Sutherland and Ghaly (1990) studied fluidized paddy drying by experiment using paddy with moisture content of 22 percent (wet basis), bed depth of 2.5 cm, and inlet air temperature of 40 to 90°C. Experimental results showed that the final moisture content of paddy was reduced to 17 percent (wet basis) and head yield percent ranged from 58 to 61 percent. But when the moisture content (in wet basis) was reduced to 16 percent (wet basis), head yield percent ranged from 15 to 24 percent. In case of reducing moisture content from 26 percent to 19 percent by drying temperature of 60 to 90°C, head yield percent ranged from 55 to 58 percent.

Tumambing and Driscoll (1991) studied fluidized paddy drying and found that the variables which affect drying capacity are temperature and bed depth.

Sripawatakul (1994) studied drying of high moisture content paddy using a continuous fluidized bed dryer. The study indicated that energy consumption was low at low specific inlet air flow rate, which further decreased with increased air recycled and weir height.

Soponronnarit and Prachayawarakorn (1994) reviewed research and development work on fluidized bed drying and conducted both experimental and simulation work on fluidized paddy drying. The results showed that the maximum drying air temperature had to be limited to 115°C and final moisture content of paddy should not be lower than 24 to 25 percent (dry basis) if product quality in terms of head yield and color were to be maintained. To maximize drying capacity and minimize energy consumption, air velocity of 4.4 m/s, bed thickness of 9.5 cm.(corresponding to specific air flow rate of 0.1 kg/s-kg dry matter of paddy) and fraction of air recycled at 80 percent should be employed.

The objective of this study was to investigate the agreement of computed data (by using developed mathematical model) and results from experiment.

MATERIALS AND METHODS

Materials

A continuous cross flow fluidized bed dryer as shown in Fig. 1 is the main equipment in this work. It consists of a backward curved blade centrifugal fan, a diesel fuel-oil burner, a drying section (length, width and height of 1, 2.5 and 1.2 m respectively), and a cyclone. The paddy bed depth was controlled by a weir. Paddy was fed in and out by rotary feeders. While in operation, hot air (temperature controlled by thermostat) was blown into the drying section through a performed steel sheet floor. The hot air and paddy run perpendicularly. A small portion of exhaust air is left in the atmosphere while the remainder, after being cleaned in a cyclone, was recycled, mixed with ambient air and then reheated to the desired temperature. The capacity of this fluidized bed dryer is 5 to 10 tons/hr.

Experimental Methods

In this study, results were obtained from a continuous fluidized bed dryer with tested capacity of 9.5 tons/hr, superficial hot air velocity of 2.33 m/s, inlet air temperature ranging from 115° to 130°C, and bed depth of 15 cm. During the experiments, paddy samples collected before and after drying were examined for moisture content and milling quality in terms of head yield and whiteness. Wet and dry bulk temperatures at various positions, as shown in Fig. 1, were measured by thermocouple (type K) connected to a data logger with accuracy of ±1° C. The quantity of diesel consumed by the burner was recorded as well. Superficial hot air velocity was measured by hot wire anemometer and compared with Pitot static tube.

Development of Mathematical Model

Sripawatakul O. (1994) developed a mathematical model for the empirical equation of mean residence time of paddy in continuous fluidization technique and on the assumption that there is thermal equilibrium between drying air and product, and the air and grain were of the plug type.

1. Equation of mean residence time

$t = hu/F$

(1) where:

t	=	mean residence time, min
hu	=	mass of paddy within the drying chamber, kg
F	=	paddy feed rate, kg/min, and
hu	=	$r_p V_p$
hu	=	$r_p(1x2.5xH)$ = $2.5\ r_p H$

(2) where:

r_p	=	average paddy density, kg/m^3
V_p	=	is paddy volume, m^3
H	=	is weir height, m

2. Drying model

Inside the drying chamber (Fig. 1), bulk paddy was divided into thin layers (assuming with n layers) The control volume of the thin layer is shown in Fig. 2. The changes in moisture content of paddy, temperature and humidity ratio of air were calculated for each layer. The following basic equations were employed.

2.1 Equation of drying rate

The empirical equation for fluidized bed paddy drying in the form of Page's equation (1949), and developed by Sripawatakul (1994) was used. The equation is as follows:

$$MR = \exp(-at^b) \qquad (3)$$

where:

$$MR = (M(t) - M_{eq})/(M_{in} - M_{eq})$$

$$a = 1.631x10^{-3}T_{mix} + (-1.162 + 4.153x10^{-3}T_{mix})(m_{mix}/hu) + ..\ 0.1474\ln(m_{mix}/hu) + 0.475$$

and

$$b = -3.22x10^{-3}T_{mix} + (-0.836 + 2.032x10^{-2}T_{mix})(m_{mix}/hu) - ..\ 0.1432\ln(m_{mix}/hu) + 0.5485$$

The symbols are defined as follows:

t	=	drying time, min
$M(t)$	=	moisture content of paddy at time t, decimal dry basis
M_{in}	=	moisture content of paddy at the inlet of drying section, decimal dry basis
M_{eq}	=	equilibrium moisture content, decimal dry basis
T_{mix}	=	air temperature at the inlet of drying section, ^{0}C
m_{mix}	=	air flow rate at the inlet of drying section, kg/s

The equilibrium moisture content was obtained from the equation developed by Laithong (1987), as follows:

$$RH = 1 - \exp[-4.723\times10^{-8}(1.8T_{mix} + 491.7)(100M_{eq})^{2.386} \quad (4)$$

2.2 Equation of mass conservation

Following the mass conservation law, it can be explained that at any layer of paddy bulk control volume, the quantity of water increase is equal to the quantity of water evaporated from paddy. The relative humidity of outlet air at each layer could therefore be calculated from the following equation:

$$W_{f(i)} = R(M_i - M_j) + W_{mix} \quad (5)$$

where:

$W_{f(i)}$ = humidity ratio of outlet air at the i^{th} layer, kg water/kg dry air
R = the ratio of dry mass of paddy to mass of dry air
Mi = moisture content of paddy at inlet i^{th} layer, decimal, dry basis
Mj = moisture content of paddy at outlet j^{th} layer, decimal dry basis
W_{mix} = humidity ratio of inlet air at i^{th} layer, kg water/kg dry air

2.3 Equation of energy conservation

2.3.1 Determination of outlet air state

Application of energy conservation law shows the change of air rate between drying control volume and ambient air. The equation can be written as follows:

$$T_{f1,i} = [Q_1/ m_{mix} + C_a T_{mix} + W_{mix} (h_{fg} - C_v T_{mix}) - W_{fi} h_{fg} - DU_p]/(C_a + W_{fi} C_v) \quad (6)$$

where:

$T_{f1,i}$ = temperature of outlet air at the i^{th} layer, ^0C
Q_1 = heat loss, kW
C_a = specific heat of dry air, kJ/kg.^0C
C_v = specific heat of vapor air, kJ/kg.^0C
h_{fg} = latent heat of moisture vaporization, kJ/kg

The average temperature (T_{fl}) and humidity ratio of outlet air from the 1^{st} to the n^{th} layers were determined by arithmetic mean.

2.3.2 Determination of inlet air state

From the law of energy conservation, the change of air enthalphy is equal to the summation of the rate of heat transfer between tube of air recycled and ambient air. Applying this to determine inlet air temperature, the equation can be written, as follows:

$$T_{f2} = [Q_2/(RC)(m_{mix}) + C_a T_{f1} + W_{f1} C_v T_{f1}] / (C_a + W_{f1} C_v) \quad (7)$$

where:

T_{f2}	=	inlet air temperature, °C
Q_2	=	heat loss, kW
RC	=	recycle air ratio = m_{RC} / m_{mix}
m_{RC}	=	mass flow rate of recycle air, kg dry air/ kg dry air
W_n	=	average humidity ratio of outlet air, kg water/kg dry air

For other calculations such as mixing of air stream and energy consumption at the fan and burner, the results can be achieved by applying the first law of thermodynamics [see Soponronnarit and Prachayawarakorn, 1994].

To calculate the humidity air state, the equation of Wilhelm (1976) was used .The calculation procedure is shown in Fig. 3.

RESULTS AND DISCUSSION

Comparison of Simulated and Experimental Results

A mathematical model was developed assuming there is thermal equilibrium between drying air and product, the appearance of air flowing through bulk paddy is uniform, the type of air and grain flow is plug flow, and fluidization behavior is complete.

Moisture Content

In case of low initial moisture content *(21-26 percent, dry basis)*

Drying operation was concerned with main operation parameters such as feed rate, drying air temperature, bed velocity, and bed height.

Fig. 4 and 6 show the final moisture content obtained from the model and from the experiment. Most values are nearly the same. The results from simulation have lower values than the experimental results. The agreement in results comparison is good.

In case of high initial moisture content *(> 26 percent, dry basis)*

A comparison of simulated and experimental results at different drying temperature is shown in Fig. 8 and 10. The results in this case showed higher values in the simulation compared to the experimental results. The agreement in data under these methods is fair.

Energy Consumption

In case of low initial moisture content *(21-26 percent, dry basis)*

The results from both simulation and experiment methods were obtained from sample data as shown in Fig. 5 and 7. The results in each sample under simulation were slightly less than the experimental results, thus the agreement under these methods is fair.

In case of high initial moisture content *(> 26 percent, dry basis)*

Fig. 9 and 11 show the comparison of results of energy consumption under the simulation and experiment methods. These show slightly higher energy consumption values of simulated results compared to experimental results. The agreement based on comparison of results is fairly good.

CONCLUSION

A mathematical model for continuous cross-flow fluidization was developed and used to predict fluidized bed behavior results in terms of final moisture content and energy consumption of paddy drying. The study used a 5 to 10 tons/hr capacity continuous cross-flow fluidized bed dryer. Two cases were studied: paddy with low and high initial moisture content.

The computed data was compared with experimental results. A comparison of final moisture content and energy consumption showed a fairly good agreement of results under simulation on the experimental method.

It is recommended that the model be developed further to investigate the optimum operating parameters such as air flow rate, fraction of air recycle, etc.

ACKNOWLEDGMENT

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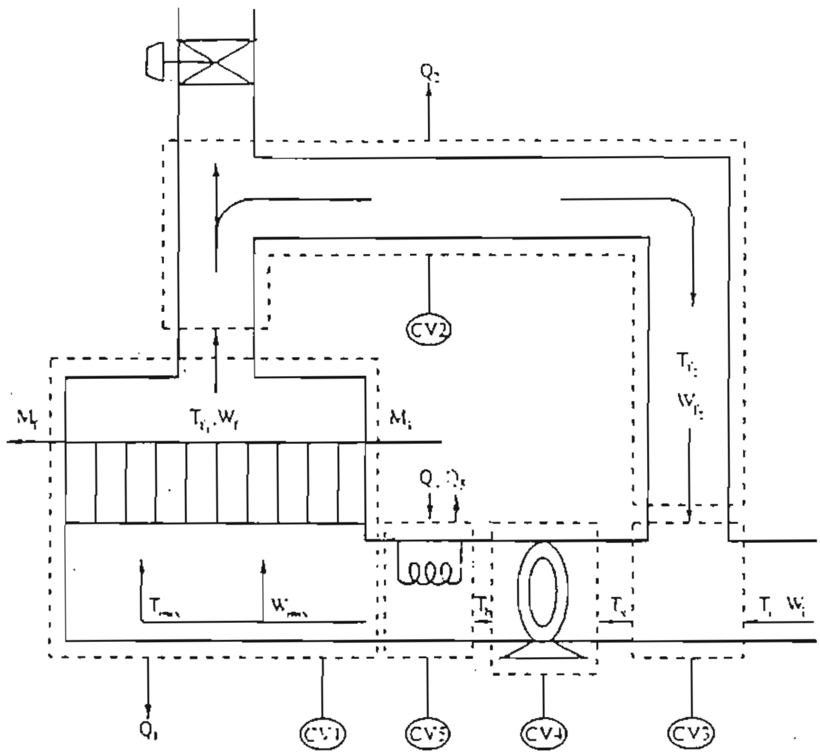

Figure 1. Control volumes of continuous fluidized bed drying system

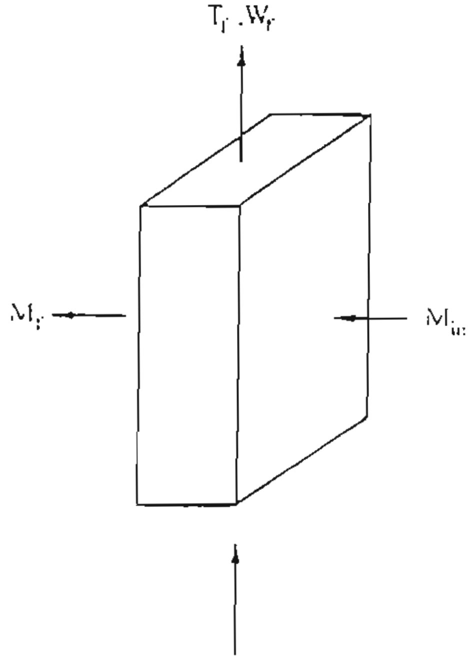

Figure 2. Control volume of the thin layer 1

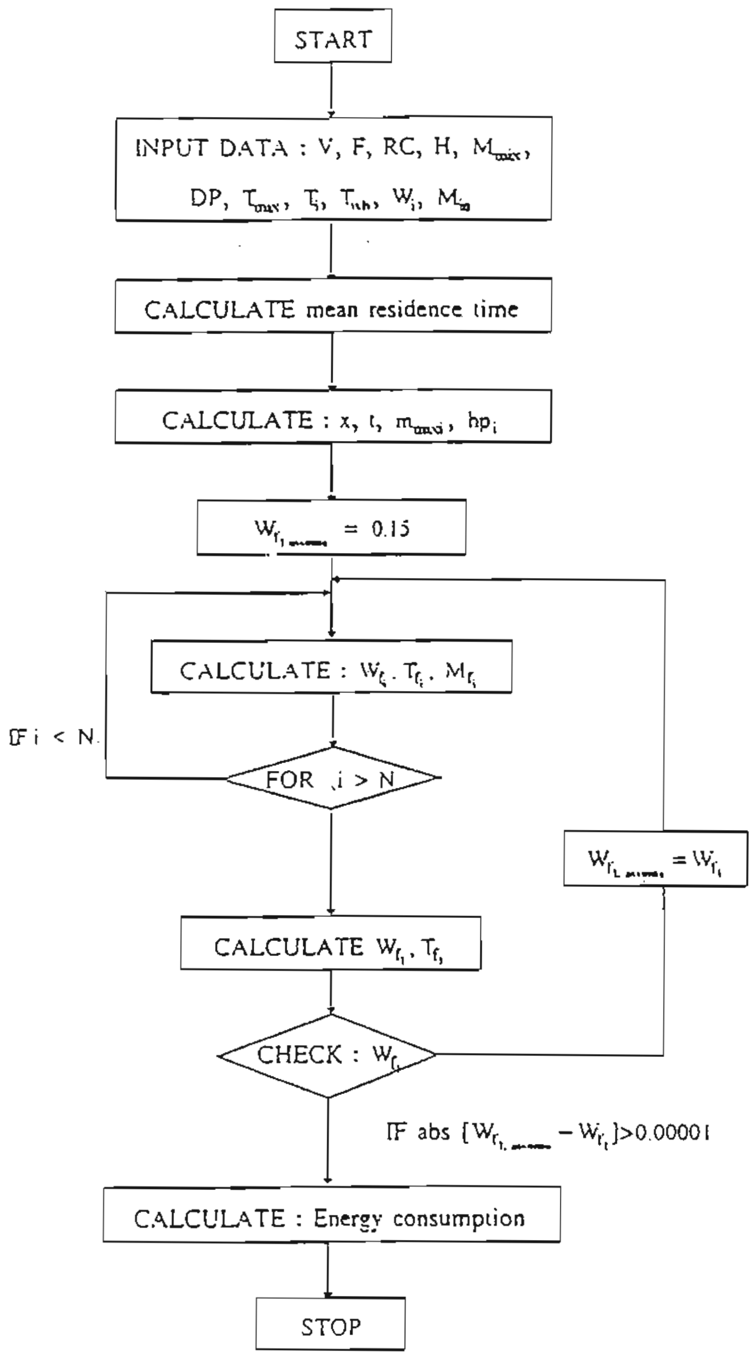

Figure 3. Computer simulation flow chart.

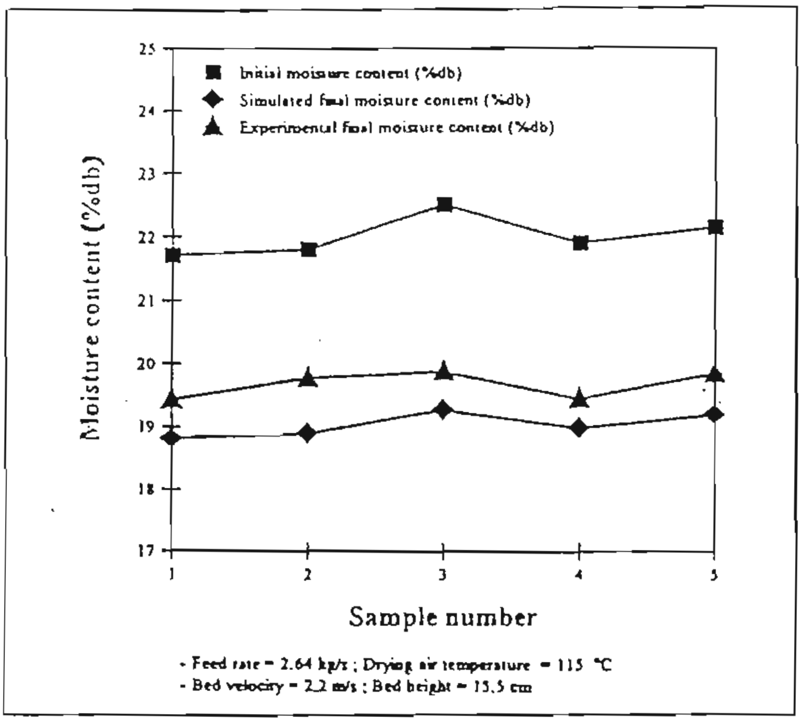

Fig. 4. Comparison between simulated and experimental moisture content

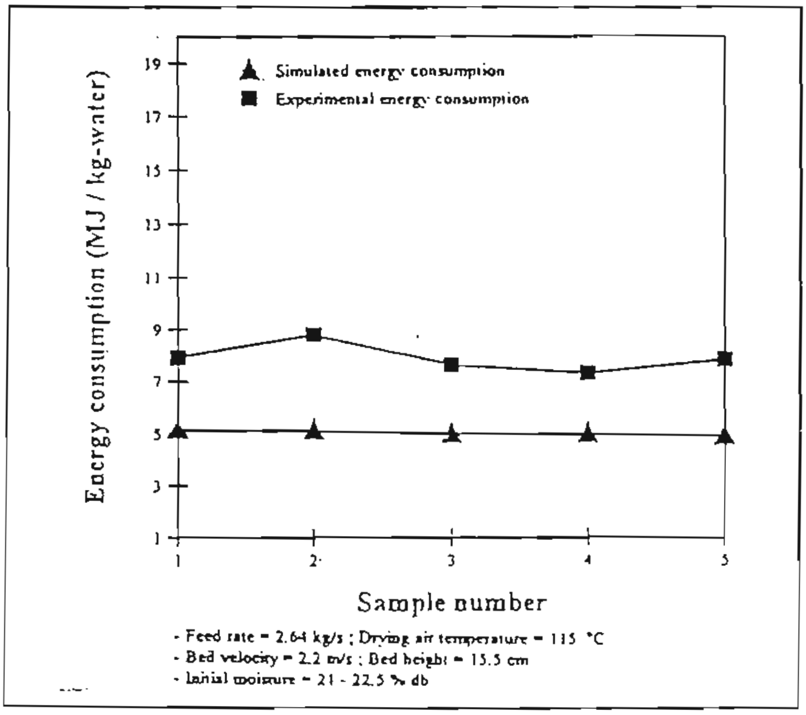

Fig. 5. Comparison between simulated and experimental energy consumptions

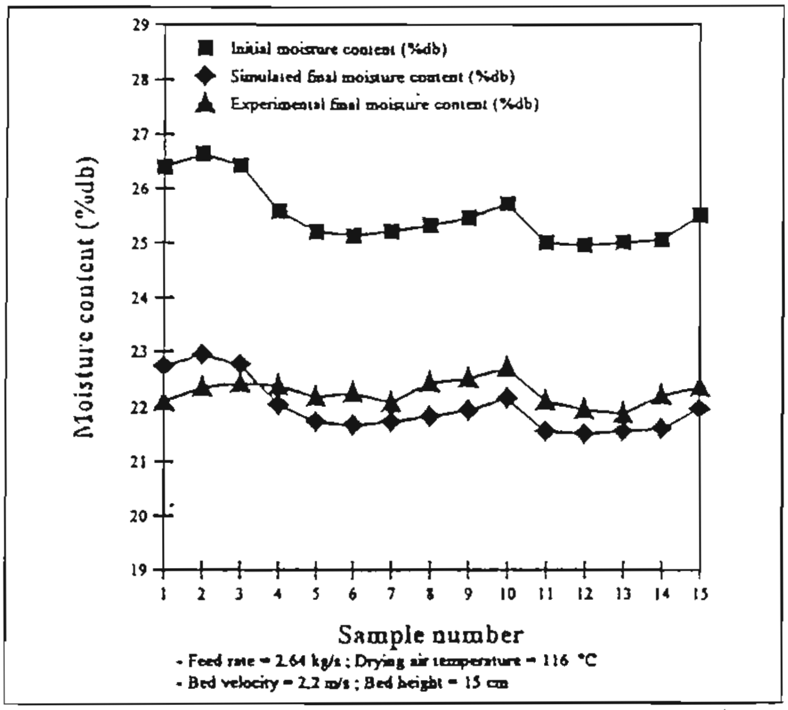

Fig. 6. Comparison between simulated and experimental moisture content

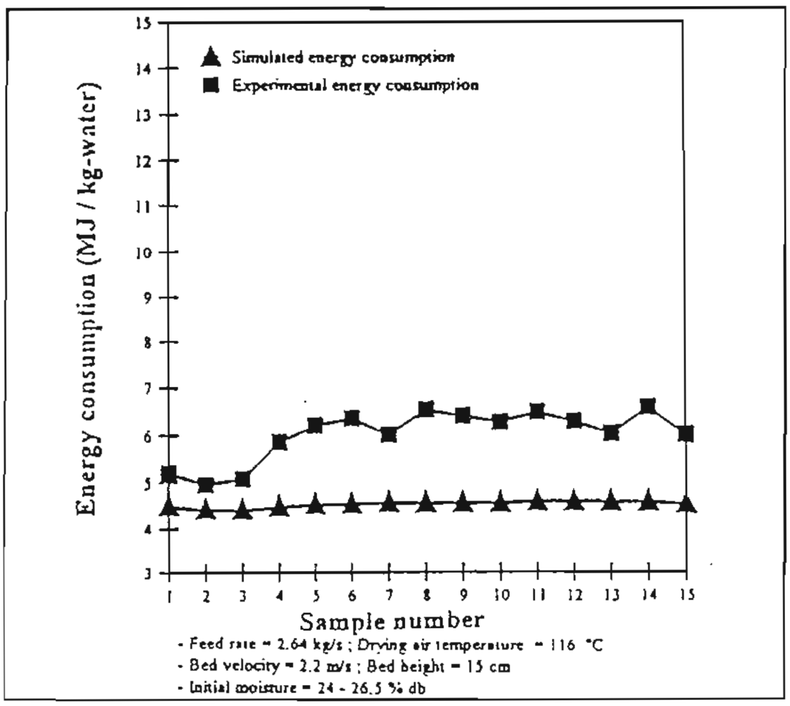

Fig. 7. Comparison between simulated and experimental energy consumptions

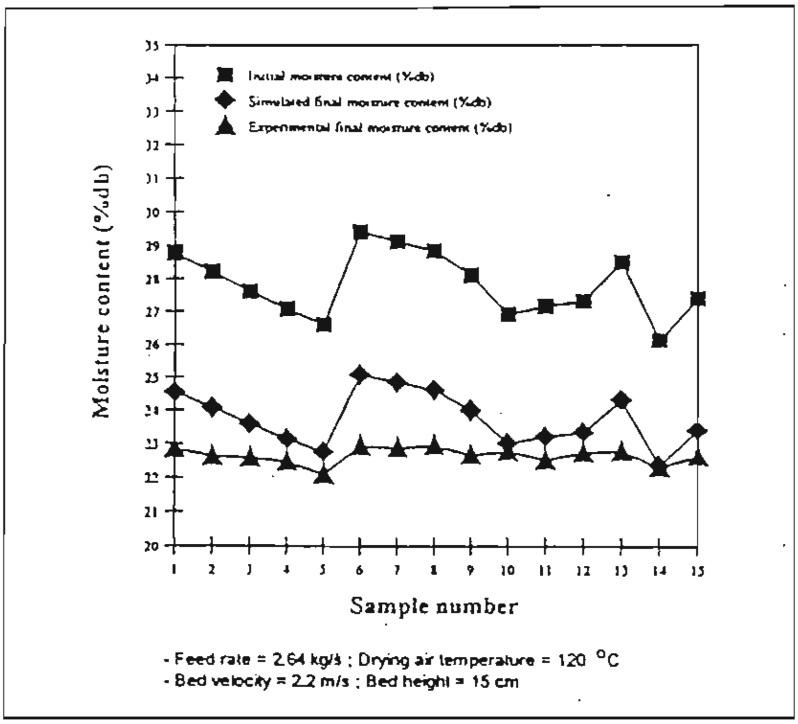

Fig. 8. Comparison between simulated and experimental moisture content

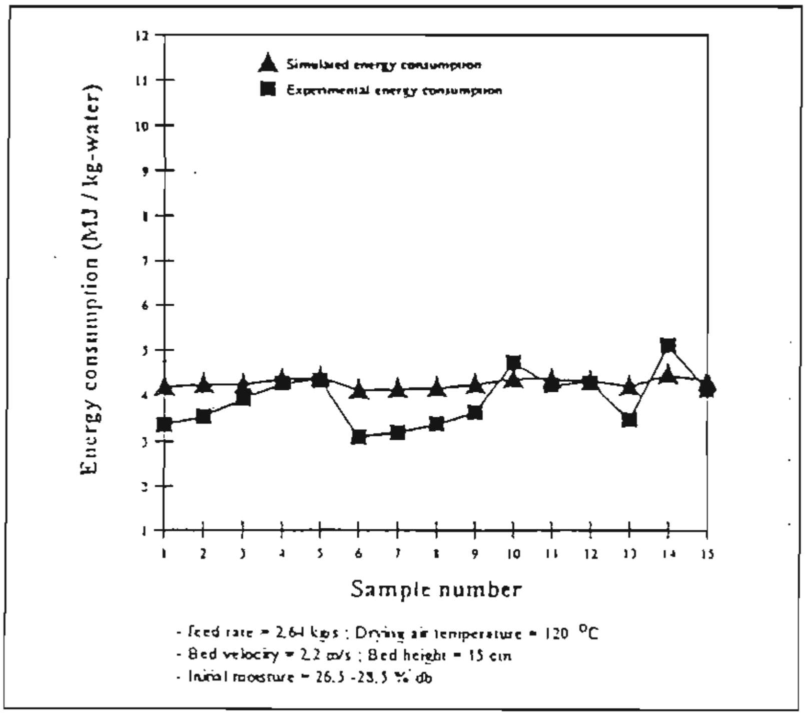

Fig. 9. Comparison between simulated and experimental energy consumptions

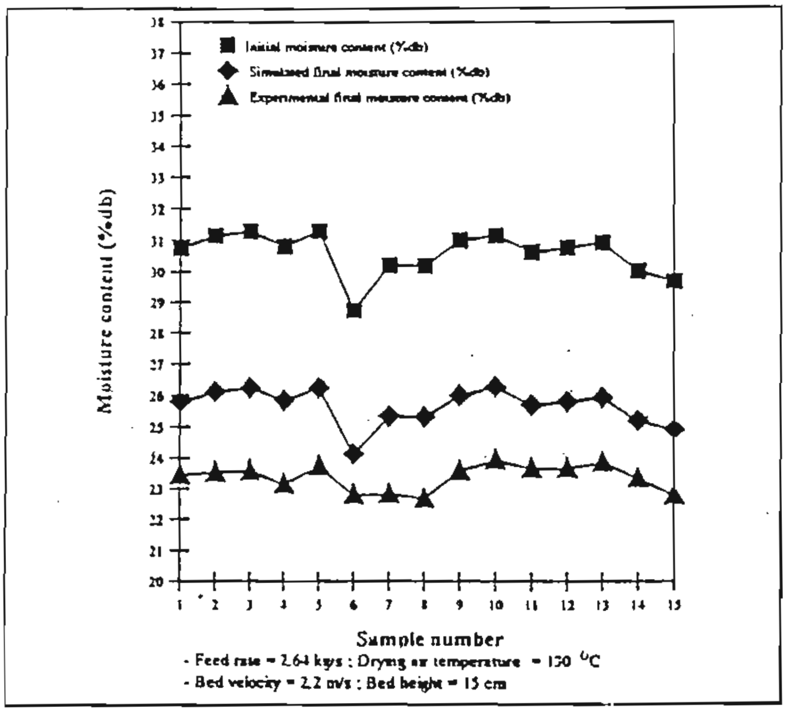

Fig. 10. Comparison between simulated and experimental moisture content

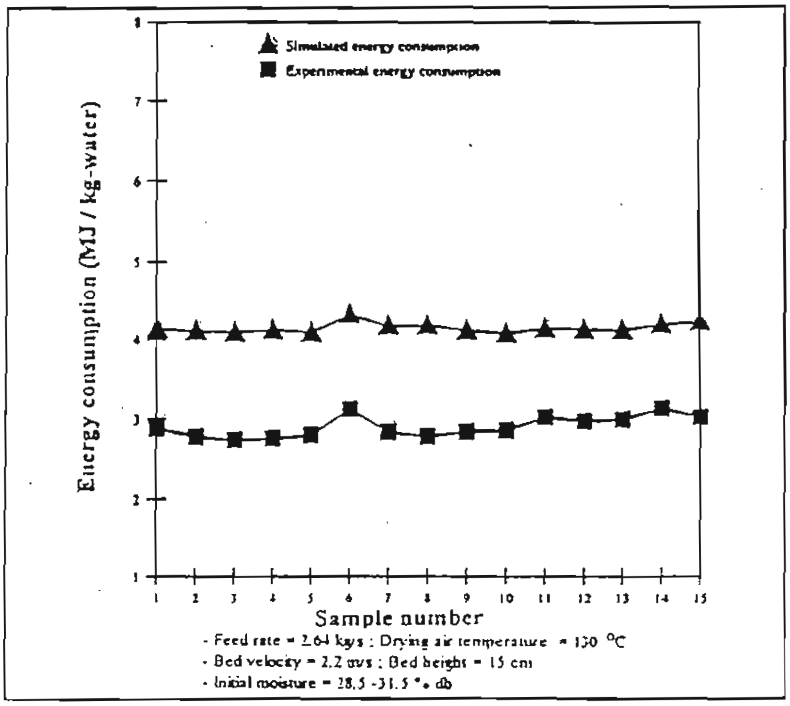

Fig. 11. Comparison between simulated and experimental energy consumptions

EXTENDED ABSTRACT

97 ISES Solar World Congress Taejon, Korea

Session # (S6-1) Oral ☑

Class.Code < - > Poster ☐

Title of Paper: DRYING OF BANANA FRUIT

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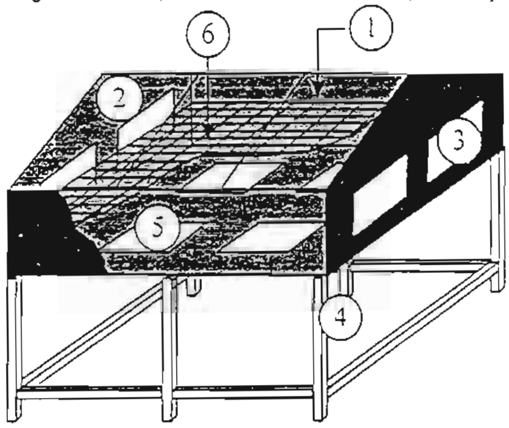
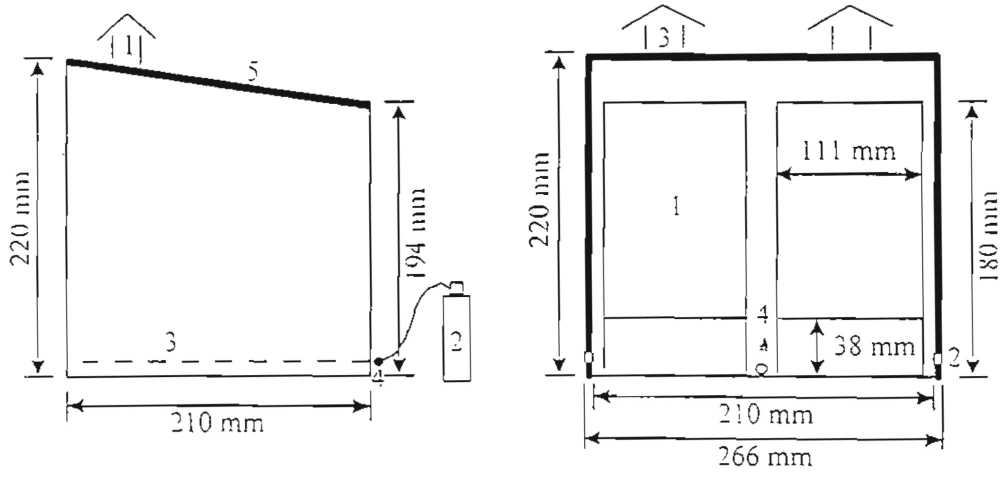
A comparative study of various method of banana drying: solar natural convection drying, LPG natural convection drying and solar forced convection drying with supplemental heat from LPG as shown in Figures 1-3, was performed at Bang-Kra-Tum, Phitsanulok Province. Experimental results showed that solar natural convection drying took 6-7 days (57 hours) for completing one batch of banana. Total primary energy consumption and the first law efficiency were about 19.2 MJ/kg of water evaporated and 11.1 % respectively. LPG natural convection drying took 3, 4 or 5 days (46, 45 or 45 hours) for completing one batch of banana. Total primary energy consumption and the first law efficiency were 8.4 MJ/kg of water evaporated and 23.6, 28.0 and 30 % respectively. The last method, solar forced convection drying with supplemental heat from LPG took 5 days (44 hours) for completing one batch of banana. Total primary energy consumption and the first law efficiency were 14.9 MJ/kg water evaporated and 15.8 % respectively. Details are shown in Table 1



1 = transparent plastic cover, 2 = plywood drying chamber, 3 = air outlet
4 = dryer legs made of wood, 5 = air inlet, 6 = bamboo tray

Figure 1 Solar natural convection dryer



1 = air outlet, 2 = LPG container 1 = trolleys, 2 = air inlet, 3 = air outlet
3 = burner, 4 = LPG valve 4 = the flame from LPG burning
5 = dryer roof

Figure 2 LPG natural convection dryer