Combustion of Leached Rice Straw for Power Generation

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To investigate the potential for using leached rice straw as fuel for existing biomass power plants, straw was fired in three different types of existing commercial boilers ranging in size from 18 to 26 MW_e: a stoker-fired traveling grate, a circulating fluidized bed (CFB), and a suspension fired unit. In each case, 33 metric tons of straw were blended 20 to 25% with the plant's standard fuel. For the grate unit the straw was blended with forest-derived wood fuel, for the CFB with a blend of urban wood and agricultural wood, shells, and pits, and for the suspension unit with rice hulls. Deposition probes were installed at the superheaters to detect changes in fouling, and stack sampling was performed to monitor changes in silica, total particulate matter, and other plant emissions. No adverse effects due to slagging or fouling were observed, and no bed agglomeration occurred in the CFB. NO_x emissions increased for the grate and CFB units due to the higher nitrogen content of the straw, and required increased ammonia injection for control. NO_x emissions did not increase for the suspension unit normally firing rice hull. The experiments demonstrate the technical feasibility of using leached rice straw as fuel in conventional power stations employing various combustion technologies.

1. INTRODUCTION

Alternatives to the open burning disposal of rice straw have long been sought in many areas of the world to reduce air pollution. Although there are many alternative uses, the energy sector represents a substantial market with the potential of consuming large quantities of straw. In some areas, such as in California, existing power generation facilities are co-located with rice production, making them attractive utilization sites for straw.

Unfortunately, rice straw, as it is available immediately following grain harvest, contains a combination of silica and potassium that leads to heavy slagging and fouling if fired in conventional combustion power plants. Chlorine in straw also accelerates corrosion in furnaces and boilers.

Potassium and chlorine are readily leached with water from biomass, including straw [1-3]. Such leaching occurs naturally when straw is exposed to rain. Leaching can also be effected through various mechanical treatments. In either case, the result is a remarkable improvement in combustion behavior leading to substantially higher ash fusibility temperatures and lower alkali and halogen volatilization [2,4,5]. Improvements to the combustion properties of rice straw via leaching have been well demonstrated in the laboratory [1,2,4]. Preliminary full scale experiments with leached rice straw were carried out successfully in a stoker-fired traveling grate boiler [6,7]. This paper describes the results of additional full scale tests for three separate biomass power technologies: stoker-fired traveling grate, circulating fluid bed, and suspension-fired boilers.

2. EXPERIMENTAL

A total of 100 metric tons (dry basis) of rain washed rice straw was collected from two commercial field sites in the Sacramento Valley during the spring of 1998 after 7 months exposure and 717 mm cumulative precipitation. Of this, 67 tonnes were hammermilled and then densified through a modified forage cuber. Half of this material was blended with a baseline wood fuel and burned in a stoker-fired traveling grate boiler, the other half was blended with an agricultural/urban wood fuel and burned in a circulating fluid bed (CFB) boiler. The remaining 33 tonnes were hammermilled and blended with rice hulls and burned in a suspension-fired boiler. For comparison, tests were also conducted in each facility using the baseline blending fuels (wood or rice hulls) without the rice straw. Because of problems feeding the suspension-fired boiler, several experiments were carried out at this facility. At the other two facilities, the straw blends were burned in single experiments without interruption. Compositions of the baseline and straw-blend fuels are listed in Table 1.

The stoker-fired traveling grate boiler was one of three identical boilers providing steam to a common header supplying three turbo-generators totaling 50 MW_e net output. The CFB boiler was a single unit with a 25 MW_e net output. The suspension-fired boiler was also a single unit with a 26.5 MW_e net output. The tests were carried out under rated load conditions with the exception of the suspension-fired unit. In that case, problems with the baghouse just before the first straw test prevented operating above 20 MW_e. All tests, including baseline, were conducted at 20 MW_e even after the baghouse was fixed. The furnace exit gas temperature (FEGT) was therefore lower than at peak load. No soot blowing occurred during testing. Operating conditions for the baseline as well as straw-blend fuel tests at each facility are listed in Table 2.

Leached straw was blended with the baseline fuel so as to make up 20 to 25% of total heating value (Table 2). During testing, samples of fuel, bottom ash, and fly ash were collected at regular intervals. Bottom ash (bed) was not continuously discharged from the CFB. To monitor potential superheater fouling, in each test a deposit probe was inserted

Table 1. Baseline and rice straw blend fuel compositions.

	Traveling Grate			Circulating Fluid Bed			Suspension-fired		
	Baseline Wood	Straw Blend	Diff. (%)	Baseline Wood	Straw Blend	Diff. (%)	Baseline Hull	Straw Blend	Diff. (%)
(% dry matter)									
C	48.92	44.73	-9	49.79	46.78	-6	39.04	39.09	0
H	5.24	4.75	-9	5.65	5.28	-7	4.77	4.77	0
N	0.34	0.51	50	0.33	0.48	45	0.43	0.48	12
S	0.04	0.07	66	0.11	0.13	18	0.07	0.13	105
Cl	0.02	0.02	15	0.03	0.03	0	0.12	0.12	2
Ash	8.00	15.55	94	5.54	11.44	106	22.36	21.96	-2
In ash (% dry matter)									
SiO_2	4.81	10.00	108	2.30	7.60	230	20.50	19.48	-5
Al_2O_3	0.94	1.70	81	0.69	1.04	52	0.09	0.34	296
TiO_2	0.05	0.08	84	0.05	0.06	32	<0.01	0.01	191
Fe_2O_3	0.48	0.83	73	0.38	0.50	30	0.06	0.18	204
CaO	0.76	1.14	51	0.86	0.78	-9	0.15	0.27	76
MgO	0.15	0.25	69	0.16	0.18	10	0.07	0.13	95
Na_2O	0.12	0.23	82	0.15	0.19	30	0.02	0.10	451
K_2O	0.26	0.43	68	0.21	0.30	39	0.72	0.62	-13
P_2O_5	0.07	0.12	77	0.10	0.12	27	0.17	0.17	-3
SO_3	0.04	0.12	162	0.22	0.23	6	0.05	0.18	244
Cl	<0.01	0.01	37	0.01	0.01	-2	0.06	0.05	-17
CO_2	0.23	0.33	40	0.29	0.23	-22	0.05	0.04	-13

Table 2. Boiler operating conditions for baseline and straw blend fuel tests.

	Traveling Grate			Circulating Fluid Bed			Suspension-fired		
	Baseline Wood	Straw Blend	Diff. (%)	Baseline Wood	Straw Blend	Diff. (%)	Baseline Hull	Straw Blend	Diff. (%)
Straw (%HHV)		23			22			20	
Steam:									
Rate (kg h^{-1})	78,500	77,800	-1	123,100	121,300	-1	73,029	67,621	-7
Pressure (MPa)	6.1	6.1	0	6.2	6.2	0	8.1	9.0	11
Temp. (°C)	485	485	0	474	476	0	477	497	4
FEGT (°C)	855	848	-1	913	917	0	805	822	2
Ammonia (kg h^{-1})	9.3	24.5	163	12.4	16.8	35	n/a	n/a	
Stack Gas									
O2 (% v/v)	6.8	7.2	6	5.7	5.5	-4	7.9	7.3	-8
NOx (ppmv)	88	82	-7	31.6	30	-5	62	54	-13
CO (ppmv)	160	111	-31	0.3	0.1	-67			
Opacity (%)	0.7	0.3	-57	4.9	6.3	29	1.0	1.1	10
SO_x (ppmv)				7.1	14.6	106			
HCl (ppmv)				16.7	19.1	14			

into the boiler just upstream of the leading superheater. The probe was a section of tube of the same SA213-T22 steel used in the plant superheaters, air-cooled to approximately the same metal temperature as the actual superheaters (500°C). After removal, deposits collected on the probes were visually inspected and then recovered by rinsing with distilled water. Rinsates were filtered and filter cake and filtrate analyzed for elemental composition. Total deposit mass was reconstructed via mass balance. Fireside deposits on superheaters and other plant equipment were also monitored visually. To test for changes in stack particulate matter emissions, filter samples were collected from the stacks during both baseline and straw blend fuel tests using a standard EPA method 5 sampling train. The traveling grate unit utilized an electrostatic precipitator (ESP) for particulate matter emission control. The other two facilities employed baghouses. The grate and CFB units used ammonia injection for NOx control, the suspension-fired unit used exhaust gas recirculation.

3. RESULTS

Principal impacts of blending straw with wood for the grate and CFB units were in the following areas: total fuel ash (Table 1) increased as a result of the higher ash content of the leached rice straw; ammonia injection rate increased to control NO_x arising from higher fuel nitrogen in the straw (Tables 1 and 2); silica concentration increased in fly ash, although this did not impact the effectiveness of the ESP; the specific deposition rate (mass per unit area per unit time) on the deposit probes decreased (Table 3); silica and chlorine concentrations increased and alkali and sulfur concentrations decreased in the deposits (Table 4). For the suspension unit firing rice hull the straw had less of an impact due to the similarity in composition of hull and leached straw. The straw evidently contained more soil than the hull as evidenced by higher aluminum, iron, and calcium concentrations in the blend (Table 1). Otherwise, the only major difficulty with straw in the suspension unit arose from the difficulty of grinding to an acceptable particle size and feeding the boiler through equipment designed for hulls.

Leached straw did not cause an increase in fouling rate nor lead to excessive slag formation. Slag was observed for some time after introducing straw to the grate boiler, but the origin of the slag is unclear. The boiler was brought up to full load from a curtailed condition just before beginning the straw test. Under thermal shock, slag already present on the wall is sometimes dislodged. Analyses of the slag composition were inconclusive and the slag discharge to the bottom ash tapered off over time during the test. No agglomeration was observed in the bed media of the CFB, and no slag was observed to form in the suspension-fired unit.

Deposit probes show that the specific rate of deposit formation decreased when firing straw. The rates are expressed on an iron free basis to remove the effects of differing corrosion rates and different amounts of probe steel in the deposits. Although the amount of straw available was limited, and the duration of the tests were short (5 to 7 h), visual observations of the superheaters are consistent with probe results in that no change in the existing deposits occurred. The decrease in deposition rates for the straw/wood blends are substantial, and are accompanied by declines in deposit alkali concentrations. The two

Table 3. Specific deposition rates (iron free) on boiler test probes.

			Deposit Mass (Fe Free) (mg)	Insertion Time (h)	Specific Deposition Rate (mg m^{-2} h^{-1})
Traveling Grate	Baseline Wood		932	7.0	2,795
	Straw Blend		594	6.6	1,894
	Diff. (%)		-36	-6	-32
Circulating Fluid Bed	Baseline Wood		2,390	4.6	10,948
	Straw Blend		893	4.6	4,091
	Diff. (%)		-63	0	-63
Suspension-fired	Baseline Hull		3,777	6.4	12,391
	Straw Blend	1	4,926	7.3	14,104
		2	1,262	4.0	6,622
	Diff. (%)*				-16

*on average of straw blend results.

Table 4. Compositions (iron free) of probe deposits.

	Traveling Grate			Circulating Fluid Bed			Suspension-fired			
	Baseline Wood	Straw Blend	Diff. (%)	Baseline Wood	Straw Blend	Diff. (%)	Baseline Hull	Straw Blend 1	Straw Blend 2	Diff. (%)*
SiO_2	6.75	15.77	134	18.71	24.51	31	54.58	58.78	34.12	-15
Al_2O_3	2.64	0.86	-67	6.63	6.97	5	0.00	0.00	0.01	89
TiO_2	0.13	0.41	208	1.00	0.46	-54	0.03	0.03	0.07	92
CaO	7.75	11.47	48	18.47	17.24	-7	0.53	0.77	0.85	52
MgO	1.50	2.42	62	5.14	3.69	-28	0.15	0.18	1.89	587
Na_2O	3.48	3.48	0	4.37	3.85	-12	0.23	0.26	0.98	169
K_2O	35.79	28.86	-19	14.83	12.88	-13	23.35	19.30	31.67	9
P_2O_5	1.65	2.81	71	2.80	2.15	-23	2.01	2.39	3.02	35
SO_3	34.49	27.35	-21	21.80	19.49	-11	8.11	8.26	14.01	37
Cl	5.18	6.56	27	3.29	7.55	129	10.96	9.93	13.22	6
CO_2	0.65	0.00	-100	2.94	1.21	-59	0.05	0.10	0.16	156

*on average of straw blend results.

tests with straw in the suspension-fired unit are inconsistent in deposition rate, being higher than baseline in one test and lower in the other. The difference likely arises from the poor control on fuel feed rate for this unit when handling straw. Chlorine concentrations increased in deposits from the straw/wood blends, but hardly changed for the straw/hull blend. The probe deposits from the CFB and suspension-fired units were more corrosive to the probe steel than the deposits from the grate boiler. The probe surface layers spalled heavily shortly after removing the probes from the CFB and suspension boilers for both baseline and straw tests.

Stack particulate matter (PM) emission rates decreased when firing straw to the grate boiler with an ESP, but increased for the CFB and suspension units employing baghouses (Table 5). The PM emission rate was higher for the CFB compared to the other two units, likely as a result of preexisting perforations in one or more bags. The suspension-fired unit also experienced some trouble with the baghouse independent of the straw tests, and the differences in PM emission rates may be routine. Filters from all three units are currently being examined to determine if an increase in emission of biogenic silica fiber occurred. The latter is of concern as a possible breathing hazard.

Table 5. Stack particulate matter concentrations (mg m^{-3} at 12% CO_2).

		Baseline Fuel	Straw Blend	Diff. (%)
Stoker-fired Traveling Grate	Mean	5.02	4.12	-18
	σ	2.17	3.16	
	COV* (%)	43.17	76.72	
Circulating Fluid Bed	Mean	37.79	54.62	45
	σ	24.5	16.74	
	COV (%)	64.83	30.65	
Suspension-fired	Mean	2.29	12.6	450
	σ	2.55	10.78	
	COV (%)	111.53	85.58	

*coefficient of variation.

4. CONCLUSIONS

Results of these full scale experiments suggest that leached rice straw is technically suitable as fuel in existing biomass boilers of various types under normal operating conditions and temperatures. Some grate slagging may have occurred as a result of recombining silica from straw with alkali from wood by blending, but the origin of the slag is unclear and the phenomenon not unknown when firing wood alone. Bed agglomeration was not observed in the CFB, and no slagging occurred in the suspension-fired unit. Specific fouling rates on simulated superheater surfaces were actually observed to decline relative to baseline fuels, although the mechanisms for this have not yet been ascertained. When blending straw with wood fuels, major impacts are the increased ash handling requirements and the need for increased fuel NO_x control (e.g. by increased ammonia injection). Deposit chlorine concentrations increased, which may contribute to increased corrosion rates, although sulfur concentrations decreased. The ESP maintained effective control of particulate matter emissions, but baghouse performance was not as clear. The composition of leached straw is similar to that of rice hull and no major differences were observed in boiler performance once fuel reached the burners. Fuel feeding was most difficult for the suspension-fired unit, of intermediate difficulty for the stokers of the traveling grate, but routine when feeding densified straw to the fuel conveyors of the CFB. Modifications to fuel feeding systems will likely be required for existing units not specifically designed for straw. Longer tests are needed to evaluate potential corrosion from leached straw addition to the fuel blend. Economic analyses are currently being developed to assess fuel and ash handling and boiler operating costs relative to potential benefits derived from nutrient recycling by leaching and reductions in open burning. Some advantages may accrue from firing straw alone as a means of recovering silica ash.

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