HYDROGEN PRODUCTION FROM HIGH MOISTURE CONTENT BIOMASS IN SUPERCRITICAL WATER

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Abstract

By mixing wood sawdust with a corn starch gel, a viscous paste can be produced that is easily delivered to a supercritical flow reactor by means of a cement pump. Mixtures of about 10 wt wood sawdust with 3.65 wt % starch are employed in this work, which we estimate to cost about $0.043 per lb. Significant reductions in feed cost can be achieved by increasing the wood sawdust loading, but such an increase may require a more complex pump. When this feed is rapidly heated in a tubular flow reactor at pressures above the critical pressure of water (22 MPa), the sawdust paste vaporizes without the formation of char. A packed bed of carbon catalyst in the reactor operating at about 650 °C causes the tarry vapors to react with water, producing hydrogen, carbon dioxide, and some methane with a trace of carbon monoxide. The temperature and history of the reactor's wall influence the hydrogen-methane product equilibrium by catalyzing the methane steam reforming reaction. The water effluent from the reactor is clean. Other biomass feedstocks, such as the waste product of biodiesel production, behave similarly. Unfortunately, sewage sludge does not evidence favorable gasification characteristics and is not a promising feedstock for supercritical water gasification.

Introduction

The goal of this work is to define conditions which enable the steam reforming of biomass (represented below as cellulose $C_6H_{10}O_5$) to produce hydrogen:

$$C_6H_{10}O_5 + 7\ H_20 \text{ --* } 6\ CO_2 + 12\ H_2.$$

Earlier work has shown that when biomass is heated quickly in water above its critical pressure, no char is formed. Instead, the biomass decomposes into simple organic molecules dissolved in the water, which further decompose to hydrogen, carbon dioxide, and some methane when exposed to a carbon catalyst at temperatures above 600 °C. In this paper we detail the conditions which evoke the biomass steam reforming chemistry, and we offer insight into the influence of the reactor's wall on the product distribution.

Apparatus and Experimental Procedures

The two flow reactors (see Figures 1 and 2) used in this work are fabricated from Hastelloy C276 tubing with 9.53 mm OD x 6.22 mm ID x 1.016 m length. The reactant flow is quickly heated by an annulus heater (located along the reactor's centerline) and an entrance heater outside the reactor to temperatures as high as 800 °C. The annulus heater (3.18 mm OD x 15.2 cm heated length) delivers all its heat directly to the feed. The entrance heater is made from a split stainless steel tube that is held in good thermal contact with the reactor, and an electrical heater which is coiled around the outer surface of the stainless steel tube. Downstream of the entrance heater, the reactor's temperature is maintained in an isothermal condition by the furnace. The chief purpose of the furnace is to prevent heat loss. In fact, in some experiments the temperature setpoint of the furnace was below the lowest temperature measured along the reactor wall. Carbon catalyst is usually packed in about 60% of the heated zone of the reactor, as well as the downstream cold section of the reactor. The reactor's temperature profile is monitored by 12 fixed, type K thermocouples held in good thermal contact with the reactor along its outer wall. Also, in reactor # 1 the reactant temperature is measured by a fixed, internal, annulus thermocouple which is located 5.08 cm upstream of the furnace (see Figure 1). Pressure in the reactor is measured by an Omega PX302 pressure transducer. A Grove Mity-Mite model 91 back-pressure regulator reduces the pressure of the cold, two phase, product effluent from 28 to 0.1 MPa. After leaving the back-pressure regulator, the reaction products pass through a gas-liquid separator. The liquid product is collected over a measured time period to calculate the liquid outlet flow rate. The gas flow rate is measured using a wet test meter.

Five different types of feedstocks are used in this work: glycerol, biodiesel waste (a mixture of methanol and glycerol), corn starch gel, poplar wood sawdust mixed in the corn starch gel, and sewage sludge mixed in the corn starch paste. Both the poplar sawdust and the sewage sludge are ground with a Wiley mill (Thomas Scientific) to 40 mesh before they are mixed with the paste. Table 1 gives elemental analyses of the feedstocks.

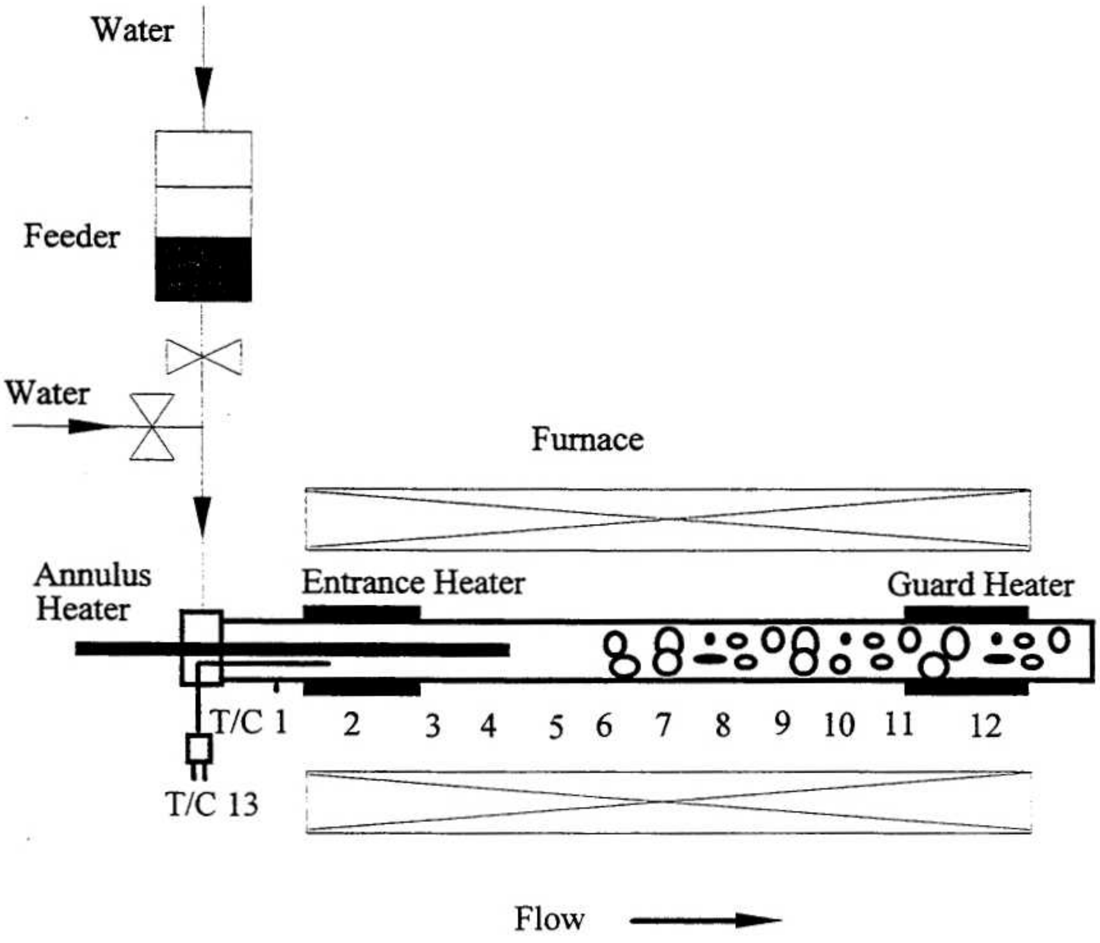

Figure 1. Reactor #1.

The feeder consists of a cylinder, a movable piston, and two end-caps (High Pressure Equipment). The cylinder is first filled with the feedstock, then the piston is placed on top of the feed, and the two end-caps are installed. Both the feeder and the reactor are pressurized separately to 28 MPa at the beginning of a run. During the time that the system is being brought up to temperature, water is pumped into the reactor by a Waters 510 HPLC pump. When the main body of the reactor reaches the desired temperature (usually about 650 °C), the feeder is connected to the reactor. Thereafter, water flow to the reactor is terminated, and water flow to the feeder is initiated, displacing the sawdust paste feedstock into the reactor. Because the thermophysical properties of the paste are considerably different than those of water; and possibly also because of exothermic pyrolysis reactions associated with the decomposition of the paste, the temperature of the feed rises very rapidly in the entrance region of the reactor. To avoid excessively high temperatures, usually it is necessary to reduce the heat input to the feed from the annulus heater and the entrance heater.

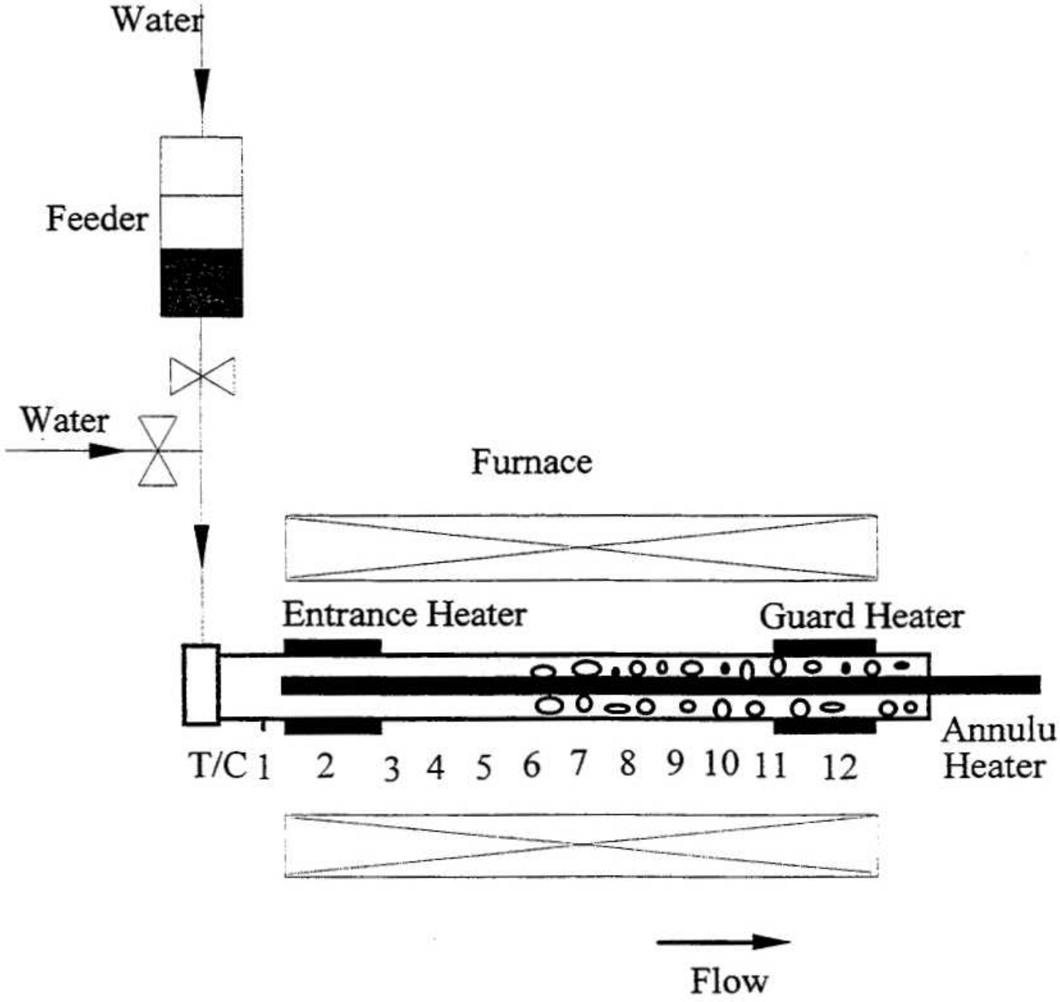

Figure 2. Reactor #2.

Gas samples are taken by gas-tight syringes from the gas sample outlet of the separator. Analysis of the gas is conducted using a Hewlett-Packard model 5890 gas chromatograph equipped with flame ionization and thermal conductivity detectors. A 80/100 mesh carbosphere molecular sieve packed column is used, operating at 35 °C for 4.2 min, followed by a 15 °C/min ramp to 227 °C, another ramp of 70 °C/min to 350 °C, and a 5 min hold at 350 °C. The carrier gas is a mixture of 8% hydrogen in helium. A standard gas mixture is used for day-to-day calibration. The TOC in the liquid effluent is determined by a Shimadzu model TOC-5000 total organic carbon analyzer.

In what follows we report gas yields as liters of gas at NTP (20 °C and 0.1 MPa) per gram of organic matter in the feedstock (L/g), and grams of gas per gram of organic matter in the feed (g/g). The reported carbon efficiency is the mass of carbon in the gas divided by the mass of carbon in the feed. Because the sawdust and sewage sludge pastes were not perfectly homogeneous, and because of variations in the gas flow rate due to unsteady release of gas by the back-pressure relief valve, the carbon efficiency occasionally exceeds 1.0 by a small amount.

The reported global mass balance is based on the flow of water and organics leaving and entering the reactor.

Table 1. Elemental Analysis of Feedstocks

	Corn Starch[1]	Poplar Wood Sawdust[2]	Digested Sewage Sludge[3]
Elemental Analysis (Dry Basis by Weight)			
C	41.1%	49.4%	N/A
H	6.5%	6.0%	N/A
O	52.4%	45.1%	N/A
N	N/A	0.06%	N/A
S	N/A	N/A	N/A
Volatile Matter	N/A	N/A	63.7%
Fixed Carbon	N/A	N/A	11.2%
Ash	N/A	0.16%	25.1%
Moisture Content[4]	12.8%	8.5%	N/A

1. The C, H, and O data were obtained from the Merck Index (5th edition, 1983).
2. The elemental analysis was conducted by Huffman Laboratories, Inc.
3. The digested sewage sludge was provided by Water Technology International Corp., Canada. The volatile matter, fixed carbon, and ash were measured following the ASTM method.
4. Moisture content was measured by placing the samples in an oven at 110°C for 8 hours.

Results

In earlier work we reported the ease of gasification of glycerol in supercritical water. Table 2 confirms the earlier result. In it we see that the hydrogen content of the gas increases from 38% to 51 % after 3.45 hr, while the methane content decreases from 20% to 11 %. During this time the total gas yield increased from 1.18 to 1.6 L/g and all the carbon in the feedstock was converted to gas. The increasing gas yield is due to the consumption of water and methane by the steam reforming reaction. Evidently this reaction is catalyzed by the reactor's wall and/or the carbon catalyst, which become more active (i.e. "seasoned") as time passes. When the gas yield reached a steady state, the feed was switched and sawdust paste was fed to the reactor for 4 hours. After this, glycerol was again fed to the reactor. Table 2 shows that the sawdust paste causes the reactor's wall and/or the carbon catalyst to lose some activity towards the steam reforming reaction.

The waste product generated by the commercial production of biodiesel fuel contains glycerol and methanol. We prepared a mixture of these two alcohols with a composition identical to that of the industrial waste. The gas produced from this mixture (see Table 3) is very rich in hydrogen, and the yield (2.05 L/g) is high. The water leaving the reactor was clean with a pH of 4-5. Evidently, this waste product is a perfect feedstock for hydrogen production.

As mentioned earlier, we prepare a sawdust paste by mixing wood sawdust into a starch gel, and this paste is easily fed to our reactors. Large quantities of wood sawdust are available at $30 per dry ton, and the quoted price of corn starch in bulk is $0.12 per pound. Using these values, the price of a 10 wt % sawdust, 3.65 wt % starch paste is $0.043 per pound. Similarly, the price of a 20 wt % sawdust, 3.65 wt % starch paste is $0.031 per pound. For comparison, the price of low sulfur coal is about $0.025 per pound.

Table 4 displays results from the gasification of corn starch gel at three different flow rates in reactor #1. Higher peak temperatures in the entrance region of the reactor were required at the higher flow rates to achieve adequate heat transfer to the reactant. In all cases, gasification was complete and the reactor gave no evidence of plugging, even after 6 hours of use. Again, the higher temperatures favorably influenced the steam reforming reaction, leading to high yields (1.7 L/g) of a hydrogen rich (48%) gas. The water leaving the reactor was clean with a pH of 7.

Sawdust paste gasification results from three consecutive runs (no intervening experiments) on different days are displayed in Table 5. In all 3 cases, the effluent water was clean with a pH of 7 to 7.5, but the reactor plugged after 2 to 3 hours on stream. Although the measured temperatures were similar on 3 and 10 July, the gas yield increased from 1.61 to 2.18 L/g, and the hydrogen content of the gas increased from 43 to 57%. Because fresh carbon catalyst was employed with each experiment, we assumed that the increase in gas yield was due to a seasoning effect of the high temperature in the entrance region on the reactor's wall. To see if the seasoned wall would provide a high gas yield at lower temperatures, we employed a lower entrance temperature in the next experiment (21 July). Remarkably, the results were effectively identical to those of the first experiment. This result, and others indicate that high temperatures are requisite to achieve high gas yields with high hydrogen concentrations from wood sawdust.

Table 2. Gas Composition from Glycerol Gasification in Supercritical Water at 28 MPa with Coconut Shell Activated Carbon Catalyst Using Reactor #2 (Exp. Date: 2/19/98)

Feedstock	18.72 wt% Glycerol in Water				
Reactor Peak Temp / Catalyst Bed temp	550°C/ 665°C				725°C/ 665°C
Flow Rate (g/min)	2.0				
Time on Stream (hr)	Before Paste[1]				After Paste[2]
	1.32	2.08	2.55	3.45	5.48
Product	Mole Fraction				
H_2	0.38	0.46	0.51	0.51	0.48
CO	0.02	0.03	0.03	0.03	0.03
CO_2	0.35	0.33	0.31	0.32	0.32
CH_4	0.20	0.13	0.12	0.11	0.16
C_2H_6	0.05	0.04	0.04	0.03	0.01
Total Gas Yield					
(L gas / g of Organics)	1.18	1.40	1.49	1.60	1.60
(g gas / g of Organics)	1.01	1.11	1.13	1.18	1.17
C Efficiency	0.96	1.00	1.00	1.01	1.01
Global Mass Balance	0.99	1.01	1.01	1.02	1.02

1. Poplar wood sawdust/corn starch paste was fed to the reactor for 4 hours after the gas generation from glycerol reached a steady state.
2. Glycerol was fed to the reactor again after the reactor plugged with the sawdust/corn starch paste.

Table 3. Gas Composition from Gasification of Glycerol/Methanol Mixture in Supercritical Water at 28 MPa with Coconut Shell Activated Carbon Catalyst Using Reactor #2 (Exp. Date: 3/13/98)

Feedstocks	Simulated Biodiesel Waste Product			
Reactor Peak Temp / Catalyst Bed Temp	730°C/ 720°C			
Flow Rate (g/min)	2.0			
Time on Stream (hr)	0.42	0.73	1.25	1.68
Product	Mole Fraction			
H_2	0.64	0.64	0.65	0.64
CO	0.05	0.05	0.05	0.05
CO_2	0.21	0.21	0.21	0.21
CH_4	0.10	0.10	0.10	0.10
Total Gas Yield				
(L Gas / g of Organics)	2.05	2.05	2.05	2.05
(g Gas / g of Organics)	1.25	1.22	1.24	1.20
C Efficiency	1.05	1.03	1.04	1.01
H Efficiency	1.43	1.41	1.44	1.38
O Efficiency	1.36	1.32	1.35	1.31
H Balance	1.04	1.03	1.04	1.03
O Balance	0.99	0.98	0.99	0.98
Global Mass Balance	0.98	0.97	0.98	0.97

Table 4. Gas Composition from Corn Starch (10.4 wt% Dry Basis) Gasification in Supercritical Water at 28 MPa with Coconut Shell Activated Carbon Catalyst Using Reactor #1 (Exp. Date: 2/20/97)

Flow Rate (g/min)	1.0			2.0			4.0		
Reactor Peak Temp / Catalyst Bed Temp	690°C/ 650°C			715°C/ 650°C			805°C/ 650°C		
Time on Stream (hr)	1.33	1.62	2.18	3.52	4.02	4.57	5.12	5.47	5.70
Product	Mole Fraction								
H_2	0.40	0.36	0.38	0.39	0.39	0.38	0.48	0.48	0.47
CO	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
CO_2	0.41	0.43	0.39	0.41	0.42	0.42	0.36	0.36	0.37
CH_4	0.18	0.20	0.22	0.19	0.18	0.19	0.14	0.14	0.14
Total Gas Yield									
(L gas/g of organics)		1.28			1.38			1.70	
(g Gas/g of Organics)	1.23	1.22	1.14	1.24	1.27	1.22	1.29	1.33	1.34
C Efficiency	1.0	1.0	0.97	1.02	1.04	1.01	1.0	1.03	1.05
Global Mass Balance	1.01	1.01	1.01	1.01	1.01	1.01	0.99	1.0	1.0

Table 6 displays results similar to Table 5 from reactor #2. In this case, we employed lower entrance temperatures on both days. As a consequence, the hydrogen content of the gas was only 27 – 30%, and the gas yield was lower (1.16 – 1.36 L/g). But in both cases, the water was clean with a pH of 7.

As mentioned earlier, plugging usually occurred with the sawdust paste after 2 – 3 hours on stream. Often we removed the plug by pumping a 1.2 M solution of hydrogen peroxide into the reactor for a short time. Table 7 gives results from the gasification of sawdust paste before and after the reactor was cleaned using hydrogen peroxide. Both the very high gas yield and the high hydrogen content were retained after cleaning. In fact, the cleaning seemed to reduce the presence of hydrocarbons in the gas.

Table 5. Gas Composition from Poplar Wood Sawdust / Corn Starch Gasification in Supercritical Water at 28 MPa with Coconut Shell Activated Carbon Catalyst on Different Dates Using Reactor #1

Experiment Date	7/3/97	7/10/97	7/21/97
Feedstocks (Dry Basis)	10.72 wt% Sawdust/ 4.01 wt% Corn Starch	11.17 wt% Sawdust/ 4.19 wt% Corn Starch	11.1 wt% Sawdust/ 4.15 wt% Corn Starch
Reactor Peak Temp / Catalyst Bed Temp	790°C/ 685°C	790°C/ 690°C	732°C/ 690°C
Flow Rate (g/min)	2.0		
Time on Stream (hr)	1.62	1.52	1.42
Product	Mole Fraction		
H_2	0.43	0.57	0.45
CO	0.03	0.04	0.03
CO_2	0.38	0.33	0.38
CH_4	0.17	0.06	0.15
C_2H_6	0.001	0.001	0.0
Total Gas Yield (L Gas / g of Organics)	1.61	2.18	1.57
(g Gas/ g of Organics)	1.37	1.65	1.48
C Efficiency	0.96	1.01	1.01
Global Mass Balance	1.01	1.00	0.99

[redacted]

Table 6. Gas Composition from Poplar Wood Sawdust / Corn Starch Gasification in Supercritical Water at 28 MPa with Coconut Shell Activated Carbon Catalyst on Different Dates Using Reactor #2

Experiment Date	12/17/97	2/12/98
Feedstocks (Dry Basis)	9.47 wt% Sawdust/ 3.55 wt% Corn Starch	10.04 wt% Sawdust/ 3.65 wt% Corn Starch
Reactor Peak Temp / Catalyst Bed Temp	750°C/ 700°C	725°C/ 700°C
Flow Rate (g/min)	2.0	
Time on Stream (hr)	1.37	1.02
Product	Mole Fraction	
H_2	0.27	0.30
CO	0.02	0.02
CO_2	0.46	0.44
CH_4	0.24	0.23
C_2H_6	0.005	0.009
Total Gas Yield		
(L/g of Organics)	1.36	1.16
(g/ g of Organics)	1.34	1.22
C efficiency	0.98	0.91
Global mass balance	0.95	0.98

Table 7. Effect of H_2O_2 Cleaning on the Gas Composition from Poplar Wood Sawdust / Corn Starch Gasification in Supercritical Water at 28 MPa with Coconut Shell Activated Carbon Catalyst Using Reactor #1 (Exp. Date: 7/10/97)

	Before Plug			After Plug and Pumping H_2O_2	
Time on Stream (hr)	0.78	1.00	1.52	2.92	3.13
Feedstock (Dry Basis)	11.17 wt% Sawdust / 4.19 wt% Corn Starch				
Flow Rate (g/min)	2.0				
Reactor Peak Temp/ Catalyst Bed Temp	790°C /690°C			805°C /690°C	
Product	Mole Fraction				
H_2	0.56	0.58	0.57	0.59	0.56
CO	0.04	0.04	0.04	0.04	0.05
CO_2	0.34	0.32	0.33	0.33	0.34
CH_4	0.06	0.06	0.06	0.04	0.05
C_2H_6	0.001	0.001	0.001	0.0	0.0
Total Gas Yield					
(L Gas /g of organics)	2.18			2.18	
(g Gas/g of Organics)	1.60	1.52	1.65	1.64	1.56
C Efficiency	0.99	0.94	1.01	0.98	0.96
Global Mass Balance	1.00	0.98	1.00	0.99	0.97

To gain further insight into the role of the reactor's wall as a catalyst for the steam reforming reaction, we wrapped the annulus heater with nickel wire. We estimate that the surface area of the wire was 30% of the surface area of the hot region of the reactor. As seen in Table 8, the results indicate that nickel has no special effect on the reaction chemistry with a entrance peak temperature of about 740 °C. Molybdenum is another important component of Hastelloy. To test its effect on the reaction chemistry, we mixed molybdenum powder with the sawdust paste and fed it to the reactor. To our surprise, the metal powder catalyzed char forming reactions which significantly reduced the gas yield, the carbon efficiency, and the global mass balance (see Table 8). The reactor plugged after less than an hour on stream. Evidently, molybdenum is not a catalyst for the gasification reactions at entrance temperatures of about 730 °C.

The results of earlier exploratory experiments led us to believe that the gasification characteristics of sewage sludge over a carbon catalyst in supercritical water would resemble those of wood sawdust. To gain more definitive insight into this matter, we devoted almost two months of effort during the past year to studies of sewage sludge gasification. These tests were frustrating. In addition to the inherent difficulty of handling sewage sludge, we found that mixtures of the sludge with starch gels were not stable unless relatively large amounts of starch were used (about equal to the amount of sludge in the mixture). Results from our most successful tests are given in Table 9. Note that in all the sewage sludge experiments we employed very high entrance temperatures to maximize gasification. Nevertheless, the gas yields from the dried Canadian. sewage sludge powder were not high, and the carbon efficiency was low. Because we were unable to learn the exact history of the Canadian sludge sample, we obtained a digested sludge from a local treatment plant for further work. Unfortunately, this sludge was less easily gasified than the Canadian sample: the gas yield was very low and it contained little hydrogen. One consequence of the low gas yield was the fact that the reactor plugged after less than one hour on stream. Some insight into the gasification chemistry can be gained by comparing the sewage sludge results with those of corn starch gel alone (see Table 9). If we imagine the sludge to be an inert additive, we would expect the gas yield to fall from about 1.4 L/g to 0.7 L/g when equal amounts of sludge and starch are fed to the reactor. In Table 9 we see that the Canadian sludge behaves as though it is almost inert. Most of the gas comes from the starch. Remarkably, the Hawaiian sludge not only does not gasify, it even destroys the favorable gasification properties of the starch. This may be due to the presence of sulfur, heavy metals, or other species in the sludge. After the experiments with the sewage sludge, we attempted reproduce some earlier results with the sawdust paste feed. This test failed. Apparently, the sludges altered the properties of the reactor's wall. For this reason, the reactor was retired and a new reactor was fabricated.

Table 8. Gas Composition from Poplar Wood Sawdust / Corn Starch Gasification in Supercritical Water at 28 MPa in a Packed Coconut Shell Activated Carbon Bed with Different Metal Catalysts Using Reactor #1

Experiment Date	2/12/98	2/19/98	12/17/97
Feedstocks (Dry Basis)	10.04 wt% Sawdust/ 3.65 wt% Corn Starch	10.5 wt% Sawdust/ 3.8 wt% Corn Starch	9.47 wt% Sawdust/ 3.55 wt% Corn Starch
Metal Catalyst	Ni Wire Wrapped Around the Annulus Heater	Mo Powder Mixed in the Feedstock	None
Reactor Peak Temp / Catalyst Bed Temp	740°C/ 715°C	730°C/ 680°C	750°C/ 700°C
Flow Rate (g/min)	2.0		
Time on Stream (hr)	1.53	0.60	1.37
Product	Mole Fraction		
H_2	0.31	0.29	0.27
CO	0.02	0.02	0.02
CO_2	0.42	0.46	0.46
CH_4	0.24	0.21	0.24
C_2H_6	0.01	0.02	0.01
Total Gas Yield			
(L Gas/g of Organics)	1.16	0.90	1.36
(g Gas/g of Organics)	1.22	0.90	1.34
C Efficiency	0.91	0.66	0.98
Global Mass Balance	0.97	0.89	0.95

Table 9. Gas Composition from the Gasification of Different Types of Sewage Sludge/ Corn Starch Feedstocks in Supercritical Water at 28 MPa with Coconut Shell Activated Carbon Catalyst Using Reactor #1

Experiment Date	9/11/97	9/19/97	10/3/97	2/20/97
Feedstocks (Dry Basis)	4.26 wt% Sewage Sludge (Canadian) /5.19 wt% Corn Starch	7.69 wt% Sewage Sludge (Canadian) /7.69 wt% Corn Starch	4.07 wt% Sewage Sludge (Hawaii) /5.06 wt% Corn Starch	10.4 wt% Corn Starch
Reactor Peak Temp / Catalyst Bed Temp	810°C/ 680°C	780°C/ 685°C	820°C/ 685°C	715°C/ 650°C
Flow Rate (g/min)	2.0			
Time on Stream (hr)	1.26	0.57	0.82	3.52
Product	Mole Fraction			
H_2	0.35	0.38	0.20	0.39
CO	0.01	0.02	0.01	0.01
CO_2	0.50	0.37	0.75	0.41
CH_4	0.14	0.22	0.05	0.19
C_2H_6	0.003	0.002	0.0	0.0
Total Gas Yield (L Gas/ g of Organics)	0.75	1.01	0.23	1.38
(g Gas/ g of Organics)	0.81	0.86	0.33	1.24
C Efficiency	0.62	0.73	N/A	1.02
Global Mass Balance	1.02	0.89	0.87	1.01

Conclusion

1. A semi-solid gel can be made from 4 wt % (or less) corn starch in water. Wood sawdust and other particulate biomass can be mixed into this gel and suspended therein, forming a thick paste. This paste is easily delivered to a supercritical flow reactor by a cement pump.
2. Above the critical pressure of water, wood sawdust can be steam reformed over a carbon catalyst to a gas composed entirely of hydrogen, carbon dioxide, methane, and a trace of carbon monoxide. There are effectively no tar or char byproducts. The liquid water effluent from the reactor has a low TOC value, a neutral pH, and no color. This water can be recycled to the reactor.
3. Trace amounts of carbon deposited in the entrance region of the reactor are easily and quickly removed by the delivery of water with some dissolved oxygen (or hydrogen peroxide) to the reactor. Some evidence suggests that this cleaning procedure may improve the performance of the gasifier.
4. The wall affects the gasification chemistry. Products from wood sawdust paste gasification decrease the activity of the wall towards hydrogen production by improving methane yields. These wall effects are strongly temperature dependent. High entrance temperatures strongly favor the methane steam reforming reaction and result in the production of a hydrogen rich gas.
5. Sewage sludge is a very problematic feedstock. Much more work is needed to learn if it is a suitable feedstock for hydrogen production. In light of the availability of biomass feedstocks that are easily gasified, we recommend that further studies of sewage sludge be postponed.

Acknowledgments

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