SundropFuels™

June 26, 2014

Laboratory Gasification Memo
Biomass Moisture Experiments

Summary

Biomass gasification experiments using SEP Southern yellow pine of two different moisture levels were completed and analyzed. The 'low moisture' biomass has a moisture content of about 9-13% by weight, and the 'high moisture' biomass has a moisture content of about 18-23% by weight. It was discovered that higher moisture contents in the biomass led to better conversion across a wide range of space times at 1350 °C.

Experimental Methods

In order to understand the effect of biomass moisture content on gasification, SEP Southern yellow pine with a high moisture content of around 18-23% was tested at conditions mirroring tests done previously on dryer SEP Southern yellow pine with a moisture content of around 9-13%. Tests were completed over a wide range of space times and biomass flow rates of two, three, and four pounds per hour.

Pressure for all tests was 50 psig and temperature of the SiC outer wall was set at 1350 °C. Steam to biomass and CO_2 to biomass ratios were held constant as entrainment nitrogen flow rate was changed to adjust the space time. Feedstock was sieved to a size of <250 μm for both dry and wet experiments. Detailed set points for all experiments can be found in Appendices A and B.

Four main results are discussed in this memo. The first is total conversion, denoted as X_{tot} in Equation 1. This is a measure of the fraction of carbon in the biomass which is converted to any gaseous product. The carbon in the entrainment CO_2 is corrected for in the inlet and outlet so that unreacted CO_2 does not contribute to conversion totals.

$$X_{tot} = \frac{\dot{n}_{Cout,gas} - \dot{n}_{C_{in,CO_2}}}{\dot{n}_{Cin,biomass}} \tag{1}$$

Good conversion, X_{good} in Equation 2, is a measure of the fraction of carbon in the biomass which is converted to either CO or CO_2 .

$$X_{tot} = \frac{\dot{n}_{Cout,CO} + \dot{n}_{Cout,CO_2} - \dot{n}_{C_{in,CO_2}}}{\dot{n}_{Cin,biomass}} \tag{2}$$

Methane yield is denoted as Y_{CH_4} in Equation 3. This equation calculates the fraction of carbon in the biomass which is converted to methane.

$$Y_{CH_4} = \frac{\dot{n}_{Cout,CH_4}}{\dot{n}_{Cin,biomass}} \tag{3}$$

Finally, tar load is given in Equation 4. It is a representation of the mass of benzene, toluene, and naphthalene measured in the outlet gas. $\dot{V}_{gas,out}$ is the volumetric flow rate of gas in standard cubic meters.

$$TarLoad = \frac{\dot{m}_{C_6H_6} + \dot{m}_{C_7H_8} + \dot{m}_{C_{10}H_8}}{\dot{V}_{gas,out}} \tag{4}$$

Results and Discussion

Conversion

Results for total and good conversions are shown in Figures 1 and 2, respectively. ANOVA on each of the results shows that both space time and moisture have a significant effect on the conversion calculations. The ANOVA tests are outlined in Tables 1 and 2. It is clear that higher moisture content in the biomass leads to a higher conversion to CO and CO_2 in the experiments performed.

Table 1: Effects on total conversion for all tests.

Effect	Prob <F
Space Time	<0.0001
Moisture	<0.0001
Space Time * Moisture	0.9067

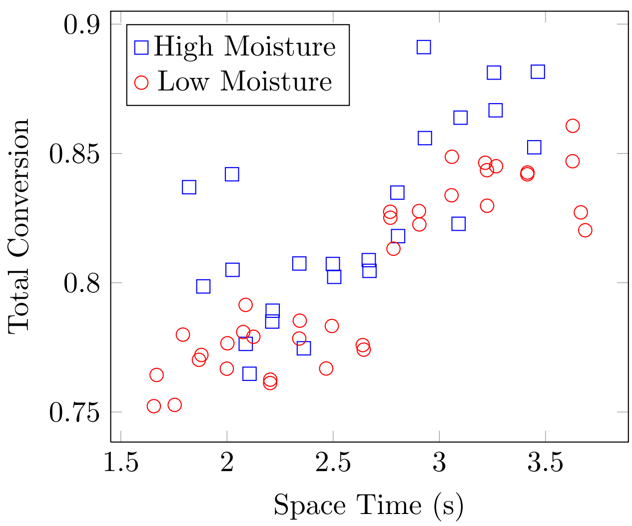

Figure 1: Total conversion for biomass moisture experiments.

Table 2: Effects on good conversion for all tests.

Effect	Prob <F
Space Time	<0.0001
Moisture	<0.0001
Space Time * Moisture	0.1620

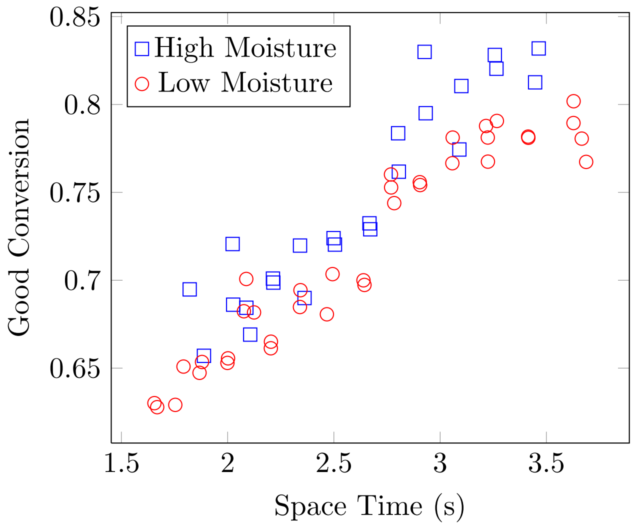

Figure 2: Good conversion calculations for biomass moisture experiments.

Table 3: Effects on methane yield for all tests.

Effect	Prob <F
Space Time	<0.0001
Moisture	0.0014
Space Time * Moisture	0.0061

Methane and Tars

Analyzing all of the tests together using ANOVA shows that higher moisture content leads to lower methane yields (Table 3) but has no effect on tar loading (Table 4). However, looking at the plots for methane yield and tar loading shown in Figures 3 and 4 suggests that the effects may be different depending on what space time regime one looks at. Previous experience has also shown that methane yield tends to be correlated with tar yields. If we see an effect on methane yield from biomass moisture, it might be expected that there is also an effect on tar yield.

Performing ANOVA separately on 2, 3, and 4 lb/hr experiments shows interesting results for methane yield and tar loads. At 2 lbs/hr, there is a negative effect on both methane and tar production from biomass moisture. At 3 lbs/hr, an effect is not statistically detectable. Then, at 4 lbs/hr, the effect from biomass moisture is posi-

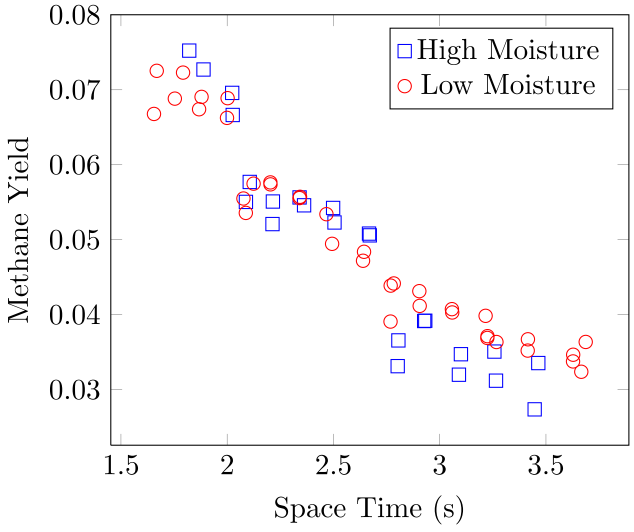

Figure 3: Methane yield results for biomass moisture experiments.

Table 4: Effects on tar loading for all tests.

Effect	Prob <F
Space Time	<0.0001
Moisture	0.1231
Space Time * Moisture	0.5562

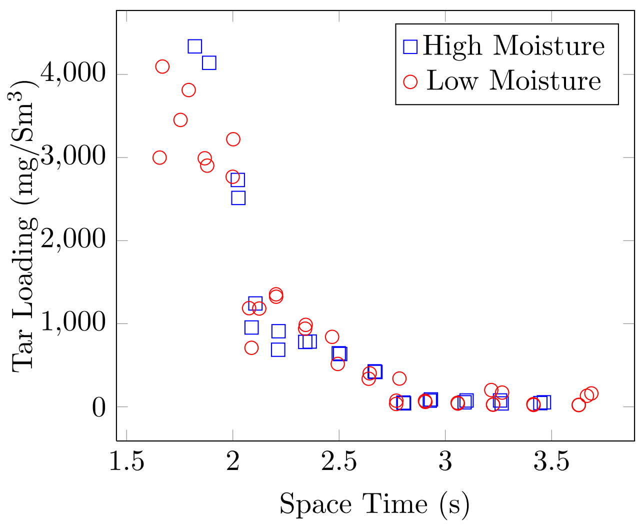

Figure 4: Tar loads for biomass moisture experiments.

Table 5: Summary of effect signs on methane yield and tar load for each biomass flow rate setpoint.

	2 lbs/hr	3 lbs/hr	4 lbs/hr
Methane	−	0	+
Tar	−	0	+

tive in both methane and tar production. These results are outlined in Table 5. All tables giving detailed ANOVA results for each biomass flow rate are given in Appendix D.

Moisture Effect on Carbon Content

It's possible that there exists some sort of bias in the moisture measurements that could lead to errors in conversion calculations. For example, if higher moisture biomass tended to read higher than the actual value while lower moisture biomass read at the actual moisture content, the calculated feed rate of carbon into the system would be lower than reality in higher moisture tests. This could lead to higher conversion calculations.

To understand if the perceived difference in conversion for higher moisture biomass is due to analysis errors instead of physical effects, we can look at the dry carbon content for each biomass sample. Each sample is tested for carbon content with included moisture content. The dry carbon content is then reported by correcting for the moisture content which is found by the Karl-Fischer titration tests. If there was a bias in the measured moisture content based on the moisture level, one would expect to be able to detect an effect of moisture level on dry carbon content.

ANOVA was run on the dry carbon contents to see if there was a difference in the means, and results are given in Table 6. The average carbon content is 54.72% on a dry basis for the low moisture tests and 55.13% for high moisture biomass. The probability that the means are different is well above an alpha value of 0.05, so it is safe to assume that moisture readings do not lead to a bias in conversion calculations.

Table 6: ANOVA results for dry carbon content for low and high moisture content biomass.

Moisture	Mean % C	Std Error	Prob >F
Low	54.72	0.19	0.164
High	55.13	0.22	

Discussion

It was found that higher biomass moisture content has a positive effect on carbon conversion. Chemically, this may be due to the proximity of surface bound water molecules to the biomass leading to faster reaction down more beneficial pathways. It is also possible that there is a physical effect in which the bound moisture may be rapidly expanded to steam, causing biomass particles to expand or fracture. This would raise the overall surface area of the biomass and lead to faster heat transfer rates.

At long space time regimes, there higher moisture content leads to lower tar and methane production. An effect is not detected at mid-range space times and reverses so that higher moisture content leads to higher levels of methane and tars at very short space times. It may be that, at high flow rates, any benefits that surface moisture has on reducing tar and methane production may be outweighed by the vaporizing moisture leading to even shorter residence times.

While results may be due to an effect from the nature of the bound moisture in the biomass, they could also be due to the fact that there was simply more steam taking part in the reactions. The inlet steam flow rates were not lowered to make up for the extra inlet water in the wet biomass. Tests should be conducted in the future which take the extra water in the biomass into account and lower the steam flow rate to ensure all tests have similar total water flow rates.

Not accounting for the extra water in these experiments also means that the effective space times for the experiments are shorter than what is being calculated. The addition of bound water which will quickly expand into steam will cause reactants to spend less time in the reactor. Performing tests where the steam flow rate is lowered to account for the bound moisture will bring the space times more in line with lower moisture tests and may make the effects of bound moisture even more apparent.

Conclusion

Experiments have shown that increasing biomass moisture content and keeping all other set points equal leads to an increase in carbon conversion. At long space times, methane production and tar yield are lowered as biomass moisture rises. However, this effect flips so that higher moisture content leads to higher methane and tar levels at short space times. It is recommended that tests be performed in the future which remove steam from the reactor inlet to take into account the extra water coming in with the biomass. Keeping total water flow rates the same across wet and dry biomass tests can help to make clear if higher conversions are caused by higher partial pressures of steam or by the physical proximity of the bound moisture to the biomass.

A Experimental Set Points Dry Biomass

Run ID	Temp °C	Moisture % wt	Biomass lbs/hr	Steam ml/min	Steam °C	Entrainment SLPM N_2	Downbed SLPM CO_2	Argon SLPM
223	1350	12.85	2	12.08	300	27.18	3.3	2
224	1350	12.85	2	12.08	300	15.10	3.3	2
225	1350	12.85	2	12.08	300	12.08	3.3	2
226	1350	11.86	2	12.08	300	18.12	3.3	2
227	1350	11.86	2	12.08	300	12.08	3.3	2
228	1350	11.86	2	12.08	300	15.10	3.3	2
229	1350	11.86	2	12.08	300	18.12	3.3	2
230	1350	11.86	2	12.08	300	21.14	3.3	2
231	1350	11.86	2	12.08	300	24.16	3.3	2
232	1350	11.86	2	12.08	300	21.14	3.3	2
233	1350	11.86	2	12.08	300	27.18	3.3	2
234	1350	10.67	2	12.08	300	24.16	3.3	2
235	1350	10.67	4	24.16	300	24.16	6.6	2
236	1350	10.67	4	24.16	300	18.12	6.6	2
237	1350	10.67	4	24.16	300	36.24	6.6	2
238	1350	10.60	4	24.16	300	36.24	6.6	2
239	1350	10.60	4	24.16	300	24.16	6.6	2
240	1350	10.60	4	24.16	300	30.20	6.6	2
241	1350	10.60	4	24.16	300	18.12	6.6	2
242	1350	10.70	4	24.16	300	30.20	6.6	2
243	1350	10.70	3	18.12	300	31.71	4.9	2
244	1350	10.50	3	18.12	300	27.18	4.9	2
245	1350	10.50	3	18.12	300	27.18	4.9	2
246	1350	10.50	3	18.12	300	18.12	4.9	2
247	1350	10.50	3	18.12	300	22.65	4.9	2
248	1350	9.29	3	18.12	300	18.12	4.9	2
249	1350	9.29	3	18.12	300	13.59	4.9	2
250	1350	9.29	3	18.12	300	13.59	4.9	2
251	1350	9.29	3	18.12	300	31.71	4.9	2
252	1350	11.07	3	18.12	300	22.65	4.9	2
253	1350	10.50	3	18.12	300	31.71	4.9	2

B Experimental Set Points Wet Biomass

Run ID	Temp °C	Moisture % wt	Biomass lbs/hr	Steam ml/min	Steam °C	Entrainment SLPM N_2	Downbed SLPM CO_2	Argon SLPM
363	1350	18.92	2	12.08	300	27.18	3.3	2
364	1350	18.92	2	12.08	300	15.10	3.3	2
366	1350	19.84	2	12.08	300	18.12	3.3	2
368	1350	19.61	2	12.08	300	15.10	3.3	2
369	1350	22.66	2	12.08	300	18.12	3.3	2
370	1350	22.66	2	12.08	300	21.14	3.3	2
371	1350	22.66	2	12.08	300	24.16	3.3	2
372	1350	19.61	2	12.08	300	21.14	3.3	2
373	1350	19.61	2	12.08	300	27.18	3.3	2
374	1350	19.61	2	12.08	300	24.16	3.3	2
404	1350	19.35	3	18.12	300	31.71	4.9	2
405	1350	19.35	3	18.12	300	27.18	4.9	2
406	1350	19.35	3	18.12	300	27.18	4.9	2
407	1350	19.35	3	18.12	300	18.12	4.9	2
408	1350	18.39	3	18.12	300	22.65	4.9	2
409	1350	18.39	3	18.12	300	18.12	4.9	2
410	1350	18.39	3	18.12	300	13.59	4.9	2
411	1350	18.39	3	18.12	300	13.59	4.9	2
412	1350	15.98	3	18.12	300	31.71	4.9	2
413	1350	15.98	3	18.12	300	22.65	4.9	2
414	1350	19.35	4	24.16	300	24.16	6.6	2
415	1350	18.39	4	24.16	300	18.12	6.6	2
418	1350	19.35	4	24.16	300	24.16	6.6	2
420	1350	18.39	4	24.16	300	18.12	6.6	2
421	1350	18.39	4	24.16	300	30.20	6.6	2

C Experimental Results

Run ID	Total Conversion	Good Conversion	Methane Yield	Tar Loading mg/Sm^3
223	0.8274	0.7602	0.03908	34.32
224	0.8419	0.7817	0.03522	31.92
225	0.8599	0.8011	0.03464	23.74
226	0.8435	0.7812	0.03690	25.42
227	0.8462	0.7887	0.03374	20.69
228	0.8426	0.7810	0.03672	22.65
229	0.8298	0.7675	0.03714	28.12
230	0.8487	0.7812	0.04030	39.07
231	0.8277	0.7558	0.04314	72.19
232	0.8338	0.7666	0.04074	48.69
233	0.8251	0.7528	0.04388	74.09
234	0.8225	0.7542	0.04117	58.91
235	0.7695	0.6467	0.06735	2991
236	0.7766	0.6556	0.06888	3220
237	0.7643	0.6278	0.07253	4095
238	0.7523	0.6301	0.06678	2999
239	0.7721	0.6535	0.06905	2902
240	0.7527	0.6291	0.06882	3452
241	0.7668	0.6530	0.06625	2768
242	0.7799	0.6509	0.07229	3812
243	0.7791	0.6817	0.05748	1183
244	0.7612	0.6613	0.05764	1354
245	0.7625	0.6650	0.05738	1325
246	0.7668	0.6806	0.05341	841.9
247	0.7853	0.6943	0.05572	986.2
248	0.7833	0.7035	0.04945	516.2
249	0.7741	0.6973	0.04839	403.1
250	0.7759	0.7000	0.04719	337.6
251	0.7914	0.7007	0.05358	710.0
252	0.7784	0.6848	0.05555	940.4
253	0.7809	0.6824	0.05550	1187

Run ID	Total Conversion	Good Conversion	Methane Yield	Tar Loading mg/Sm^3
363	0.8349	0.7836	0.03314	51.24
364	0.8524	0.8126	0.02738	44.71
366	0.8667	0.8203	0.03120	41.18
368	0.8816	0.8319	0.03355	54.29
369	0.8812	0.8282	0.03508	76.50
370	0.8638	0.8105	0.03473	76.35
371	0.8911	0.8299	0.03916	74.20
372	0.8228	0.7744	0.03200	54.58
373	0.8180	0.7618	0.03657	41.79
374	0.8559	0.7950	0.03920	89.21
399	0.8132	0.7439	0.04417	340.0
400	0.8195	0.7666	0.03634	161.3
401	0.8272	0.7806	0.03239	132.7
402	0.8450	0.7906	0.03636	171.2
403	0.8464	0.7878	0.03985	201.8
404	0.7764	0.6843	0.05504	954.6
405	0.7892	0.6987	0.05509	909.7
406	0.7850	0.7009	0.05209	686.9
407	0.8023	0.7203	0.05230	635.2
408	0.8074	0.7197	0.05564	781.0
409	0.8072	0.7240	0.05424	644.0
410	0.8046	0.7290	0.05058	419.2
411	0.8087	0.7324	0.05082	427.1
412	0.7648	0.6691	0.05771	1244
413	0.7746	0.6899	0.05459	785.2
414	0.7986	0.6570	0.07270	4140
415	0.8050	0.6861	0.06664	2514
420	0.8419	0.7206	0.06958	2730
421	0.8369	0.6948	0.07522	4338

D ANOVA Results

Table 7: Effects on methane yield for 2 lb/hr tests.

Effect	Prob <F
Space Time	<0.0001
Moisture	0.0001
Space Time * Moisture	0.4605

Table 8: Effects on tar loading for 2 lb/hr tests.

Effect	Prob <F
Space Time	0.2853
Moisture	0.0280
Space Time * Moisture	0.6986

Table 9: Effects on methane yield for 3 lb/hr tests.

Effect	Prob <F
Space Time	<0.0001
Moisture	0.6059
Space Time * Moisture	0.0918

Table 10: Effects on tar loading for 3 lb/hr tests.

Effect	Prob <F
Space Time	<0.0001
Moisture	0.2829
Space Time * Moisture	0.3581

Table 11: Effects on methane yield for 4 lb/hr tests.

Effect	Prob <F
Space Time	0.0638
Moisture	0.0277
Space Time * Moisture	0.7186

Table 12: Effects on tar loading for 4 lb/hr tests.

Effect	Prob <F
Space Time	0.0024
Moisture	0.0110
Space Time * Moisture	0.0170