June 6, 2014

Laboratory Gasification Memo
Mixing Cup Temperature Experiments

Summary

An experimental campaign has been completed which explored the effect of inlet reactant temperature on biomass gasification. Space times were varied between 1.5 and 3.0 seconds, and mixing cup temperatures of the reactants were varied between 168 and 281 °C. Initial analyses suggest that higher mixing cup temperatures led to increased conversion to carbon monoxide and carbon dioxide as well as lower methane production.

Experimental Methods

This experimental campaign was designed as a two factor full factorial which examines two levels each of mixing cup temperature set point and space time. Two replicates of the experimental matrix were run to give sufficient statistical power to limit the risk of not detecting differences in means of 4% in the measured CO and CO_2 yield. A center point was run and replicated three times estimate variance in results.

Steam to biomass, CO_2 to biomass, and argon to biomass ratios were kept the same throughout the experimental campaign. Inlet steam temperature and total nitrogen flow were changed to match desired mixing cup temperatures and space times given in Table 1. In calculating the mixing cup temperature, adiabatic mixing between the species in the gas phase in all reactor inlets were assumed. Because of the difficulty in estimating the rate of heat transfer between the solid biomass and hot steam right at the exit of the lance as it enters the hot reactor, the heat capacity of biomass is not accounted for in these calculations. This means the mixing cup temperatures calculated in this report are likely somewhat higher than actuality.

Reactor outer wall temperature was varied between 1350 °C and 1450 °C, and pressure was 50 psig for all experiments. Feedstock was 250 μm dry Southern yellow pine SEP. At the time of writing this memo, duplicates for 1.5 second experiments as well as a midpoint run were yet to be completed at 1350 °C. Detailed set points of interest for each experiment can be found in Appendix A. Biomass properties for each run are given in Appendix B.

Table 1: Setpoints for mixing cup temperature and space time explored in the experimental campaign.

Mixing Cup Temp K	Space Time seconds
554	1.5
554	1.5
498	2.2
441	3.0
441	3.0

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 .

Table 2: Effect significance for total conversion.

T (°C)	Effect	Prob <F
1350	Space Time	0.0176
	Mixing Cup	0.1119
	Space Time * Mixing Cup	0.9425
1450	Space Time	<0.0001
	Mixing Cup	0.0018
	Space Time * Mixing Cup	0.0159

Table 3: Effect significance for good conversion.

T (°C)	Effect	Prob <F
1350	Space Time	0.0015
	Mixing Cup	0.0391
	Space Time * Mixing Cup	0.8446
1450	Space Time	<0.0001
	Mixing Cup	0.0001
	Space Time * Mixing Cup	0.051

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

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.

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

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.

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

Results and Discussion

Conversion

Total and good conversion results from the experiments completed are shown in Figures 1 and 2, respectively. A linear model was fitted to the results using a least squares fit with space time and mixing cup temperature as parameters, as well as an interaction effect term between the two. The plots show that higher mixing cup temperatures lead to higher conversion rates at similar space times.

Different models were fitted to each set of experiments run at 1350 °C and 1450 °C. While the conversions may not necessarily be a linear function of space time and mixing cup temperature, running ANOVA on the effects can give a good indication of which effects have statistical significance on the conversions. Table 2 gives results for total conversion, and Table 3 gives results for good conversion. Effects which had statistical significance using an alpha of 0.05 are highlighted in red.

For total conversion, the mixing cup temperature does not have a statistically significant impact on total conversion at 1350 °C, while it does have an impact on total conversion for experiments run at 1450 °C. However, mixing cup temperature affects the good conversion results for both 1350 °C and 1450 °C.

Methane Yield

Methane yield is calculated as the fraction of carbon in the biomass that is converted into methane in the product stream. Figure 3 shows that higher mixing cup temperatures may lead to lower methane yields at each 1350 °C and 1450 °C. Running tests to detect statistical significance on the same parameters as before shows that there is a significant effect on methane yield from the mixing cup temperature at 1350 °C but not at 1450 °C. However, it's important to note that the probability that there is an impact from mixing cup temperature is very close to the alpha value of 0.05 in both cases. Thus, we can conclude that the mixing cup temperature has an effect on methane yield at both temperatures with about a 95% certainty.

Tar Loading

Tar loading is expressed as the mass of tar in mg in a standard cubic meter of gas. Figure 4 shows results from the experiments. Note that the y-

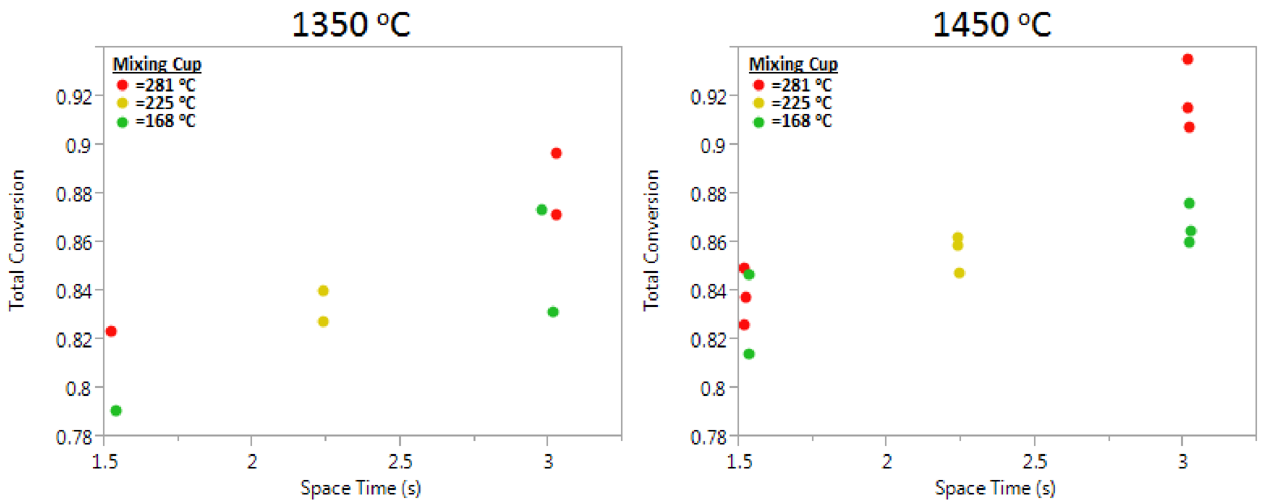

Figure 1

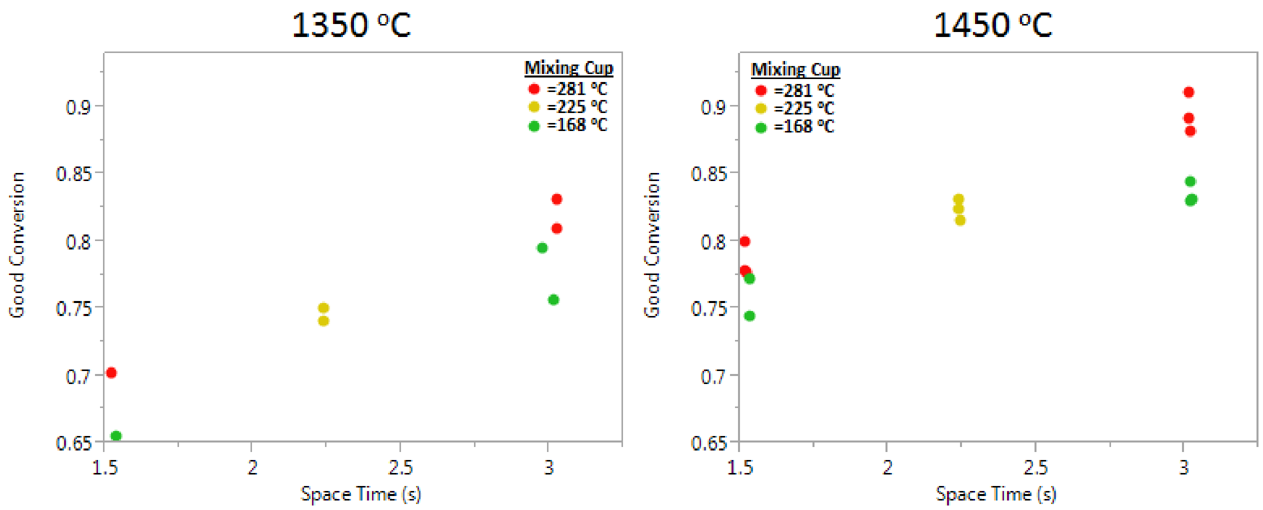

Figure 2

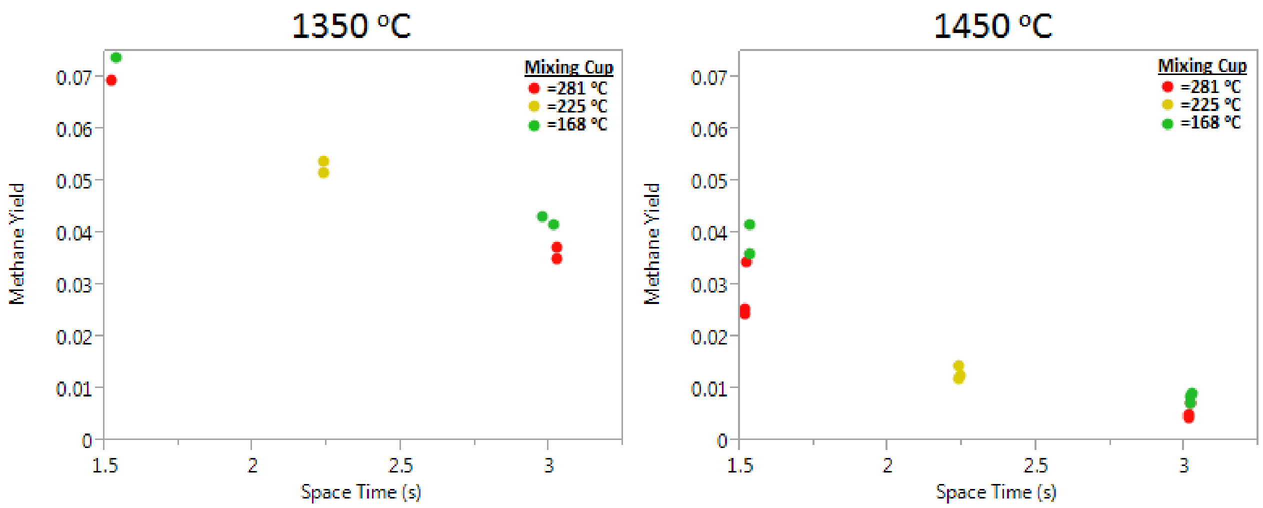

Figure 3

Table 5: Effect significance for tar loading.

T (°C)	Effect	Prob <F
1350	Space Time	0.0114
	Mixing Cup	0.4719
	Space Time * Mixing Cup	0.4841
1450	Space Time	0.0988
	Mixing Cup	0.3054
	Space Time * Mixing Cup	0.2320

Table 4: Effect significance for methane yield

T (°C)	Effect	Prob <F
1350	Space Time	<0.0001
	Mixing Cup	0.0495
	Space Time * Mixing Cup	0.8322
1450	Space Time	<0.0001
	Mixing Cup	0.0530
	Space Time * Mixing Cup	0.2476

axis for each plot is on a different scale, and the tar levels at 1450 °C are much lower than those at 1350 °C. This is a typical difference based on previous experiments run at these temperatures. Table 5 shows that there is not a statistically significant effect on tar loading from the mixing cup temperature. However, the tar levels at 1450 °C are already so low that any differences may be hard to detect on our system. Also, longer space times at 1350 °C have historically showed lower tar loadings. It would be interesting to revisit these results once the 1.5 second space time replicate experiments are completed at 1350 °C to see if a difference is detected at the shorter space time.

Conclusion

The experimental campaign explored the effects of mixing cup temperature at the inlet to the reactor for selected space times. Higher mixing cup temperatures led to a higher good conversion at both 1350 °C as well as 1450 °C. While lower methane yields may be attributed to higher mixing cup temperatures, effects on tar loading are not detected. Further exploration of shorter space time ranges which are known to produce significant tars may reveal an effect on tar loading and may even give more light to the magnitude of the effect on methane yield at these space times, as well.

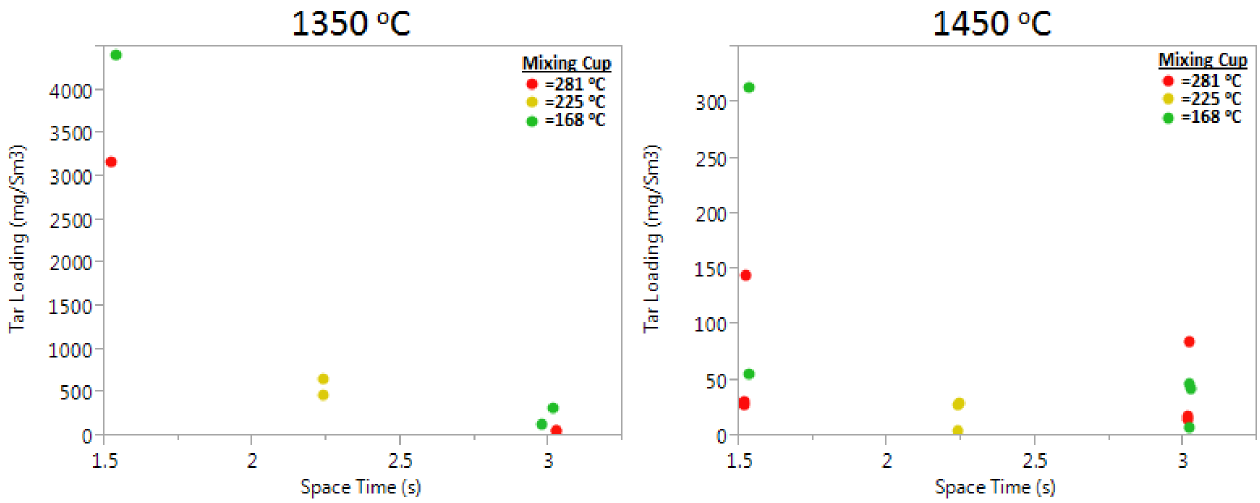
1350 °C
Mixing Cup
=281 °C
=225 °C
=168 °C
Tar Loading (mg/Sm3)
4000
3500
3000
2500
2000
1500
1000
500
0
1.5
2
2.5
3
Space Time (s)
1450 °C
Mixing Cup
=281 °C
=225 °C
=168 °C
Tar Loading (mg/Sm3)
300
250
200
150
100
50
0
1.5
2
2.5
3
Space Time (s)

Figure 4

A Experimental Set Points

Run ID	Temp °C	Biomass lbs/hr	Steam ml/min	Steam °C	Entrainment SLPM N_2	Downbed SLPM CO_2	Makeup SLPM N_2	Argon SLPM
473	1450	4	24.16	500	24.16	6.60	0	2.0
474	1450	2	12.08	500	12.08	3.30	0	1.0
476	1450	2	12.08	350	12.08	3.30	8	1.0
477	1450	3	18.12	400	18.12	4.95	0	1.5
478	1450	2	12.08	500	12.08	3.30	0	1.0
479	1450	4	24.16	350	24.16	6.60	16	2.0
481	1450	2	12.08	350	12.08	3.30	8	1.0
482	1450	3	18.12	400	18.12	4.95	0	1.5
484	1450	4	24.16	500	24.16	6.60	0	2.0
489	1450	4	24.16	350	24.16	6.60	16	2.0
490	1450	3	18.12	400	18.12	4.95	0	1.5
495	1450	4	24.16	500	24.16	6.60	0	2.0
496	1450	2	12.08	350	12.08	3.30	8	1.0
497	1450	2	12.08	500	12.08	3.30	0	1.0
500	1350	4	24.16	500	24.16	6.60	0	2.0
501	1350	2	12.08	500	12.08	3.30	0	1.0
502	1350	3	18.12	400	18.12	4.95	0	1.5
503	1350	4	24.16	350	24.16	6.60	16	2.0
504	1350	2	12.08	350	12.08	3.30	8	1.0
505	1350	2	12.08	500	12.08	3.30	0	1.0
506	1350	2	12.08	350	12.08	3.30	8	1.0
507	1350	3	18.12	400	18.12	4.95	0	1.5
508	1350	4	24.16	350	24.16	6.60	16	2.0
509	1350	3	18.12	400	18.12	4.95	0	1.5
510	1350	4	24.16	500	24.16	6.60	0	2.0

B Biomass Properties

Run ID	Moisture % wt	Carbon % wt
473	7.20	54.06
474	7.20	54.06
475	7.20	54.06
476	7.20	54.06
477	7.20	54.06
478	7.20	54.06
479	7.20	54.06
480	7.20	54.06
481	7.20	54.06
482	7.20	54.06
484	7.20	54.06
489	7.49	54.06
490	7.20	54.06
495	6.68	54.06
496	6.68	54.06
497	7.49	54.06
500	6.94	54.06
501	8.61	54.06
502	8.61	54.06
503	6.94	54.06
504	7.49	54.06
505	8.61	54.06
506	8.61	54.06
507	8.61	54.06
508	7.49	54.06
509	6.94	54.06
510	6.93	54.06

C Variable Definitions

Variable Name	Description
$\dot{m}_{Cin,i}$	Mass flow rate of species i into the system.
$\dot{m}_{Cout,i}$	Mass flow rate of species i out of the system.
$\dot{n}_{Cin,i}$	Molar flow rate of carbon into the system in species i.
$\dot{n}_{Cout,i}$	Molar flow rate of carbon out of the system in species i.
$\dot{n}_{Cout,gas}$	Molar flow rate of carbon out of the system in all gaseous species.
X_{good}	Total conversion of carbon in biomass into gaseous species.
X_{tot}	Conversion of carbon in biomass to CO and CO2 .
Y_{CH_4}	Methane yield.