SundropFuels™

September 4, 2014

Laboratory Gasification Memo
Enthalpy Experiments

Summary

In order to obtain an understanding if the main driving force for conversion of biomass to syngas is driven by residence time or heat transfer limitations, an experimental matrix was designed to examine different levels of space time and the maximum possible enthalpy change of the reactants.

Experimental Methods

Design of Experiment

It was desired to create a two factorial matrix with a center point with the two axes representing maximum residence time ($t_{res,max}$) and maximum enthalpy change (ΔH_{max}). The matrix can be seen in Figure 1. Partial pressure of steam and partial pressure of CO_2 was held constant for these experiments at 7 psi and 30 psi, respectively. These values were chosen because a large number of previous gasification experiments had partial pressures of CO_2 and H_2O near these values.

Because of the large number of possible set points in the laboratory gasifier system that would effect both the space time and maximum enthalpy simultaneously, it would have been difficult to manually design this experimental matrix. To aid in the design, a large number of potential gasifier experiments were simulated using Sundrop Fuels' gasifier analysis software suite. First, a flow rate of CO_2 was randomly assigned using a uniform distribution with a minimum possible flow rate of 3 SLPM and a maximum flow rate of 6.6 SLPM. The partial pressure of CO_2 was set at 7 psi, and the appropriate flow rate of steam to lead to a partial pressure of 30 psi was found with Equation 1.

The flow rate of Argon was set at 2 SLPM for all experiments. Biomass flow rate was randomized uniformly between 2 lbs/hr and 4 lbs/hr. The total flow rate of entrainment gas was set to be 6 SLPM for every 1 lb/hr of biomass, which was found to be a good minimum entrainment flow rate in previous experiments using the brush feeder. The remainder of the entrainment gas which isn't CO_2 is nitrogen.

Steam temperature is set at 500 °C, and makeup nitrogen is uniformly randomized between 0 and 20 SLPM. The total pressure is found using the partial pressure of steam and the total flow rate of gas into the system (Equation 2). The maximum residence time and the maximum enthalpy change were calculated for each simulated run using Sundrop Fuel's gasifier analysis software. Experiments which could not be run due to system limitations were removed from the potential runs, and enthalpy and maximum residence time targets were chosen to maximize the change in each measure. Set points for all experiments are outlined in Appendix A.

$$\dot{n}_{H_2O} = \dot{n}_{CO_2} \times \frac{P_{H_2O}}{P_{CO_2}} \tag{1}$$

$$P_{tot} = P_{H_2O} \times \frac{\dot{n}_{tot}}{\dot{n}_{H_2O}} \tag{2}$$

Calculations

Two measures of carbon conversion are discussed in this memo. The first is the fraction of carbon in the biomass which is converted to either CO or CO_2, as these are the two species which are the precursor to synthetic liquid products in the planned commercial process. This measure is refered to as "carbon yield", although it has been referred to in the past as "good conversion," and is given in Equation 3.

$$Y_{CO+CO_2} = \frac{\dot{n}_{CO,out} + \dot{n}_{CO_2,out} - \dot{n}_{CO_2,in}}{\dot{n}_{C_{biomass},in}} \tag{3}$$

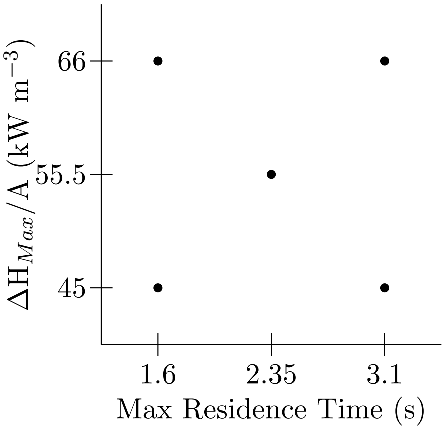

Figure 1: Two factorial experimental matrix used to vary maximum residence time and maximum ΔH between experiments.

The second measure is "carbon release", which has been referred to in the past as "total conversion." This is calculated using Equation 4 and is a representation of the fraction of carbon in the biomass which is converted to any gaseous specie.

$$X_C = \frac{\dot{n}_{C_{gas},out} - \dot{n}_{CO_2,in}}{\dot{n}_{C_{biomass},in}} \tag{4}$$

Results and Discussion

Carbon Yield

Carbon yield results are plotted in Figures 2, 3, 4, and 5. ANOVA results are given in Table 1, and factors which had a statistically significant effect on carbon yield are highlighted in red. At 1350 °C, minimum residence time was not statistically significant while $\Delta H_{Max}/A$ was. Both minimum residence time and $\Delta H_{Max}/A$ were statistically signficant at 1450 °C. However, as shown in the aforementioned plots, higher residence times led to lower carbon yields, if there was an effect. Since this is the reverse of what would be expected, it's possible that the effect did not exist, or another factor was correlated with the changing residence times that is causing the difference in calculated carbon yields. Further tests may be held in the future holding different factors constant to see if the effect seen goes away at 1450 °C.

Table 1: ANOVA results on effects of designed experimental campaign for carbon yield.

Effect	Prob <F 1350 °C	Prob <F 1450 °C
$t_{res,min}$	0.1845	0.0059
$\Delta H_{Max}/A$	<0.0001	0.0002
$t_{res,min} \times \Delta H_{Max}/A$	0.5060	0.9646

Table 2: ANOVA results on effects of designed experimental campaign for carbon release.

Effect	Prob <F 1350 °C	Prob <F 1450 °C
$t_{res,min}$	0.1175	0.0017
$\Delta H_{Max}/A$	0.0005	0.0002
$t_{res,min} \times \Delta H_{Max}/A$	0.8289	0.7615

Carbon Release

Carbon release results are plotted in Figures 6, 7, 8, and 9. Results from ANOVA reflected what was seen in carbon yield measurements. The total maximum enthalpy load was a significant factor in the carbon release at both 1450 °C and 1350 °C. Again, while minimum residence time was statistically significant at 1450 °C, longer residence times actually gave lower conversions. Since this result is the opposite of what should be expected for longer residence times, further tests may be completed in the future to see if some other factor correlated with the changing residence times was causing the apparent dependency of conversion on residence time.

Table 3: ANOVA results on effects of designed experimental campaign for tar loading.

Effect	Prob <F 1350 °C	Prob <F 1450 °C
$t_{res,min}$	<0.0001	0.0654
$\Delta H_{Max}/A$	0.0015	0.8029
$t_{res,min} \times \Delta H_{Max}/A$	0.0002	0.2309

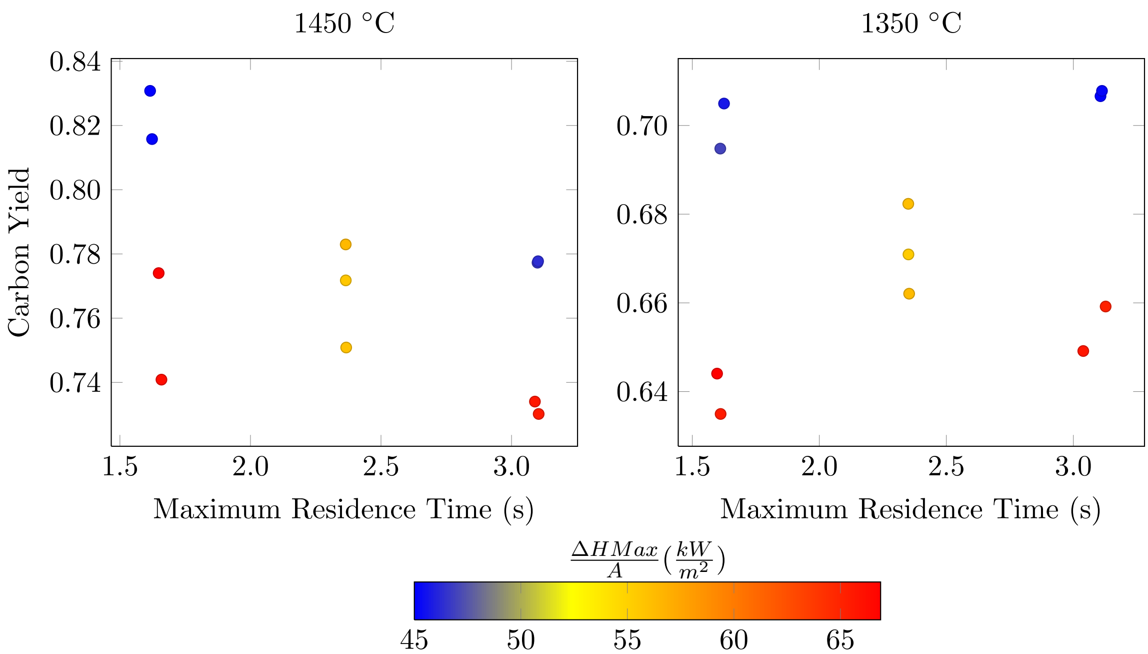

Figure 2: Blah blah blah blah SDPFOICJPFOIJD

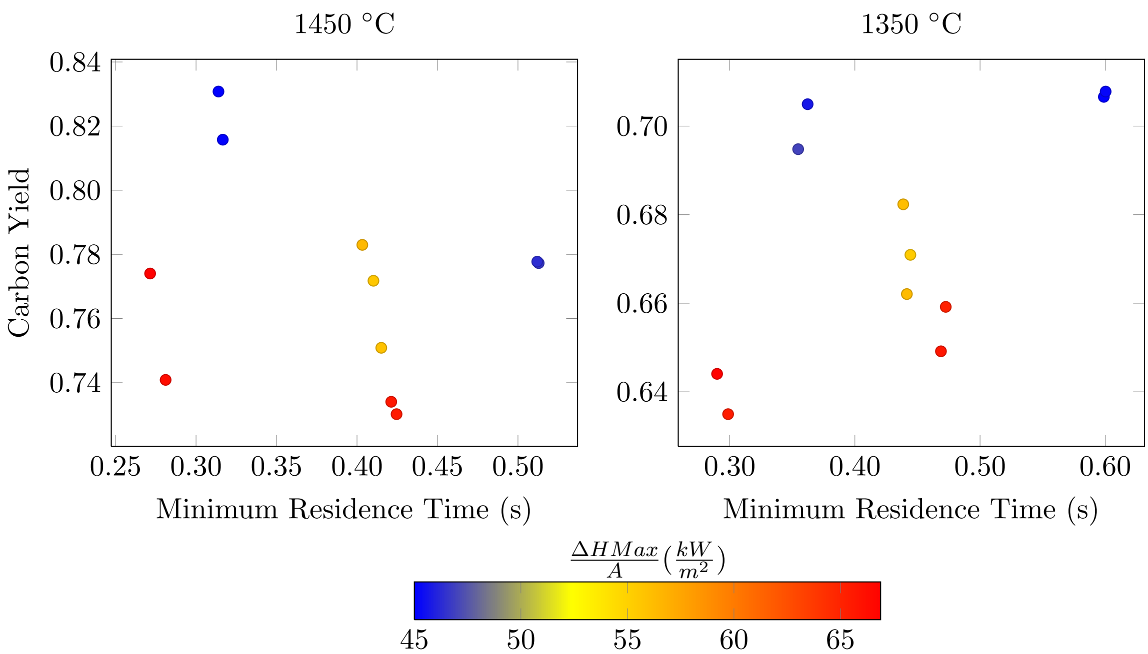

Figure 3: Blah blah blah blah SDPFOICJPFOIJD

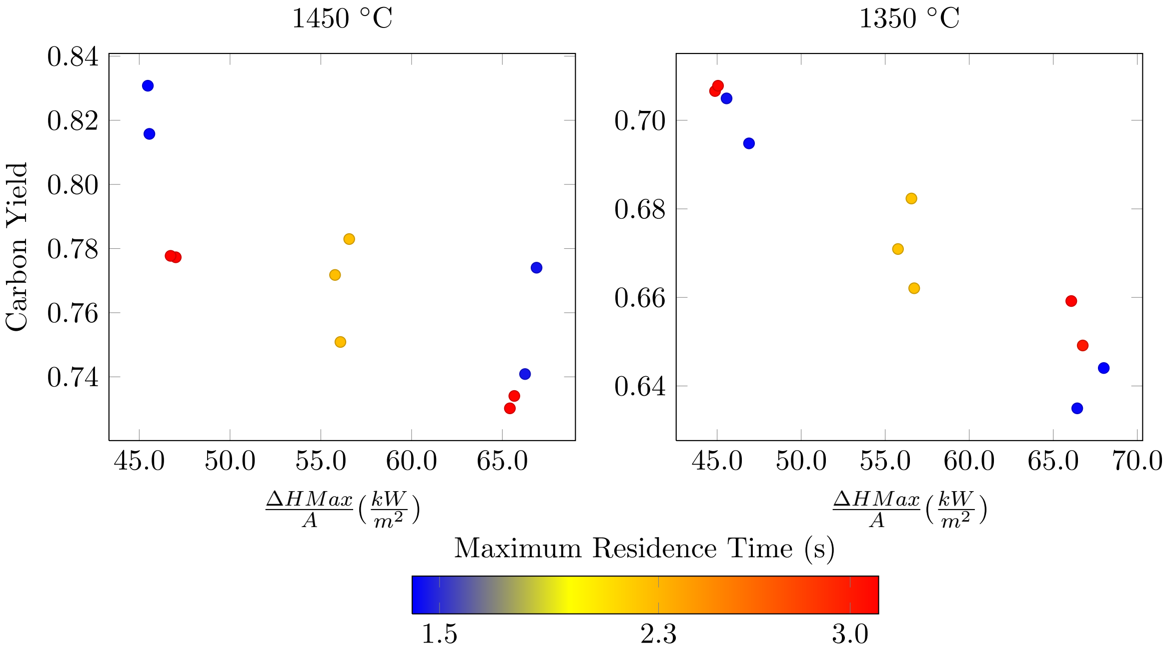

Figure 4: Blah blah blah blah SDPFOICJPFOIJD

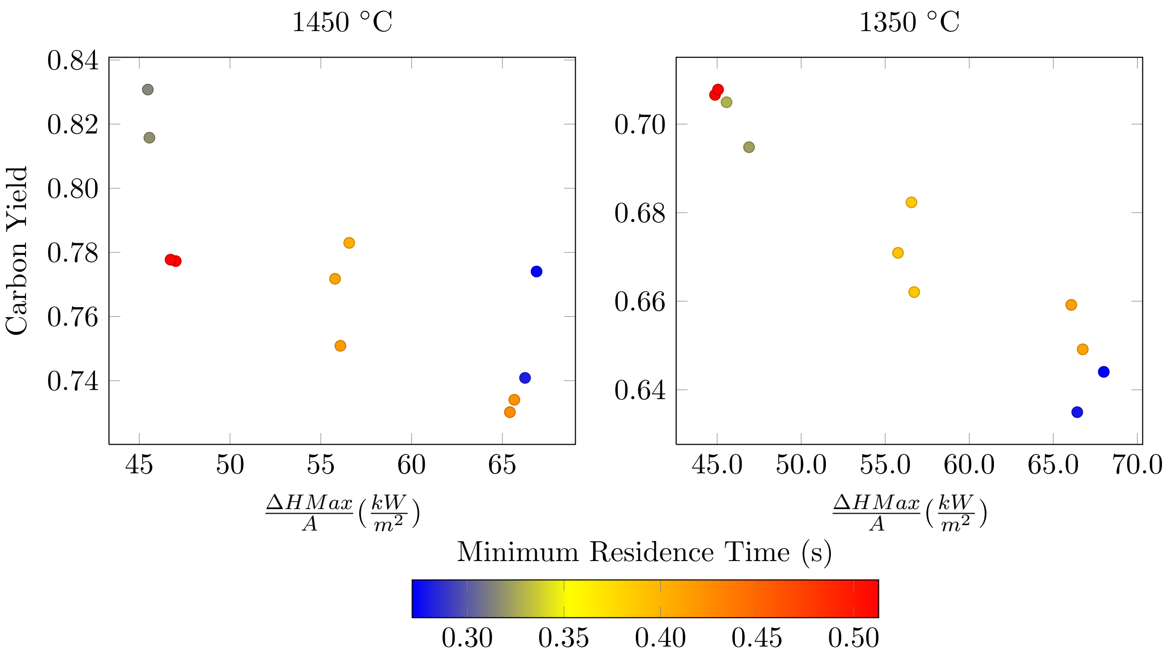

Figure 5: Blah blah blah blah SDPFOICJPFOIJD

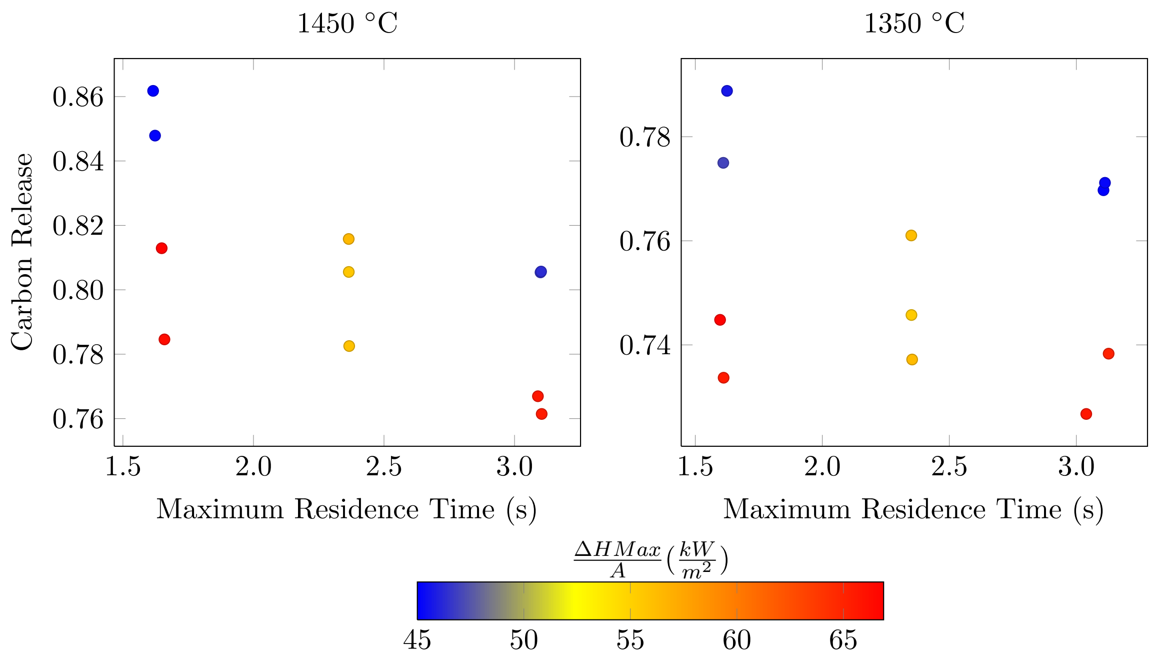

Figure 6: Blah blah blah blah SDPFOICJPFOIJD

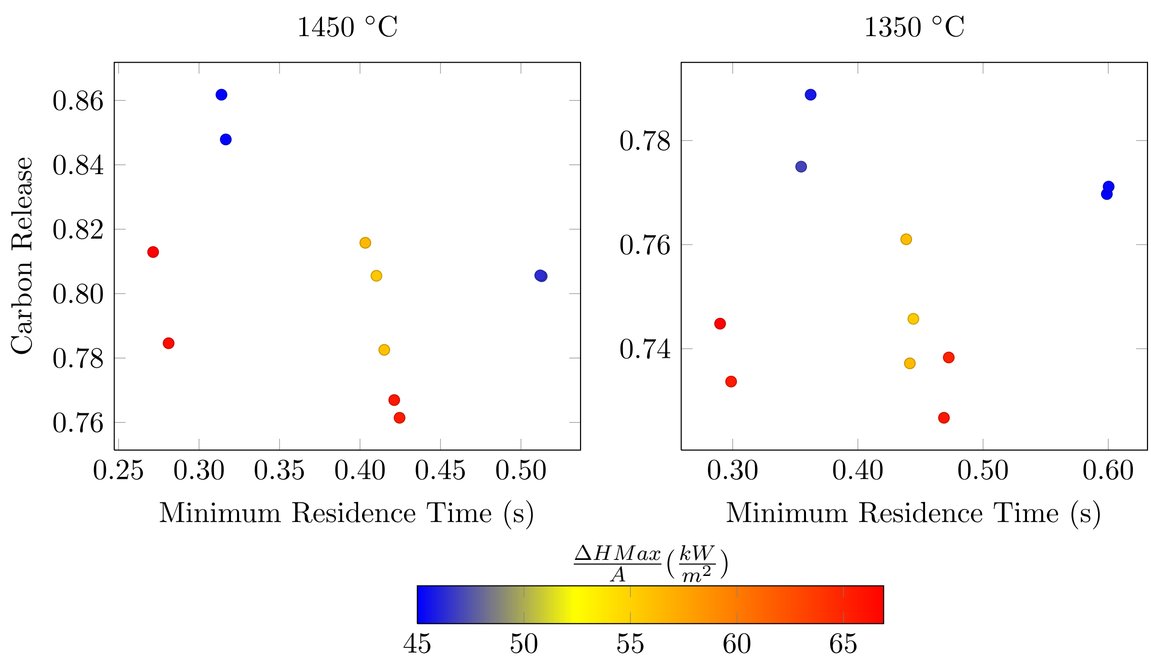

Figure 7: Blah blah blah blah SDPFOICJPFOIJD

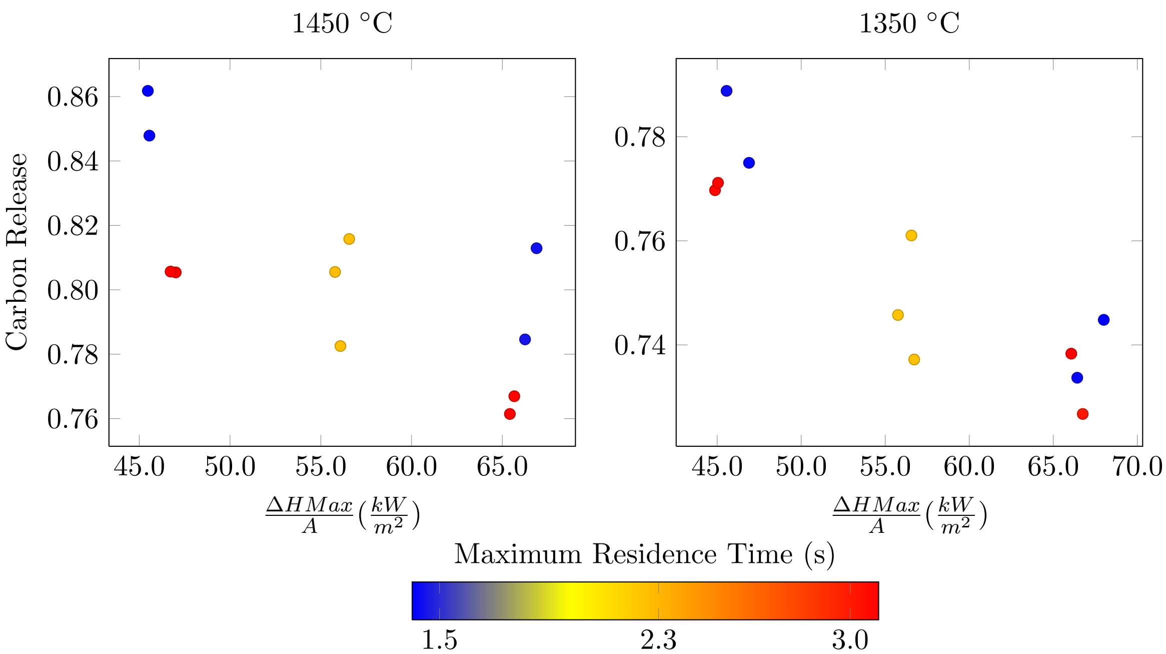

Figure 8: Blah blah blah blah SDPFOICJPFOIJD

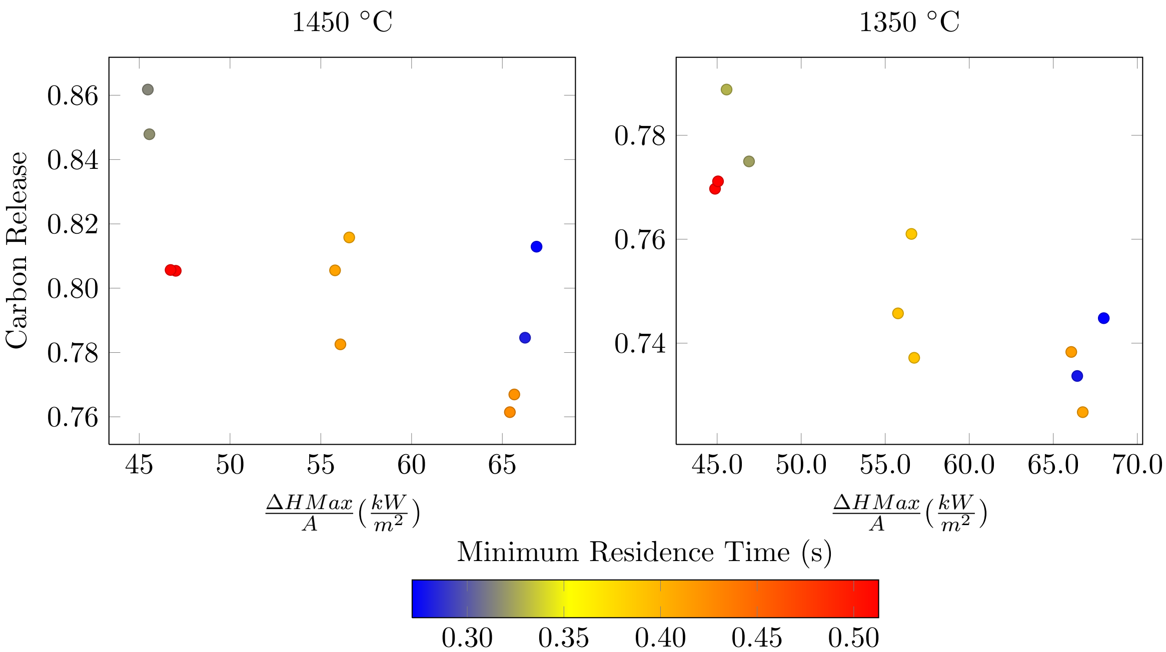

Figure 9: Blah blah blah blah SDPFOICJPFOIJD

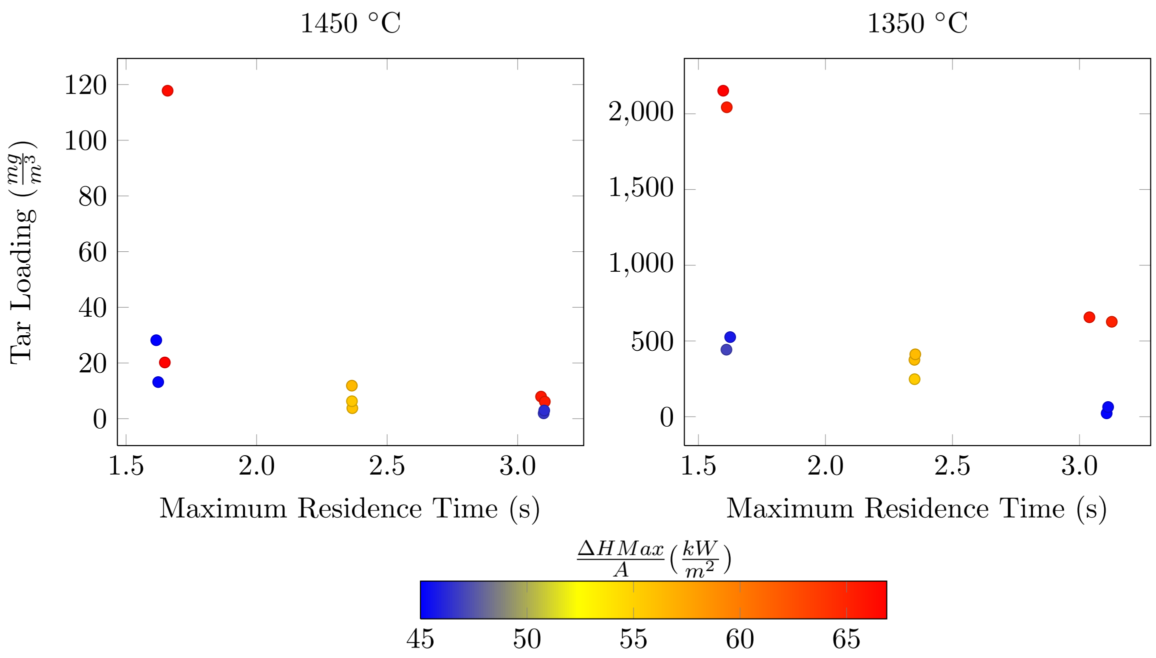

Figure 10: Blah blah blah blah SDPFOICJPFOIJD

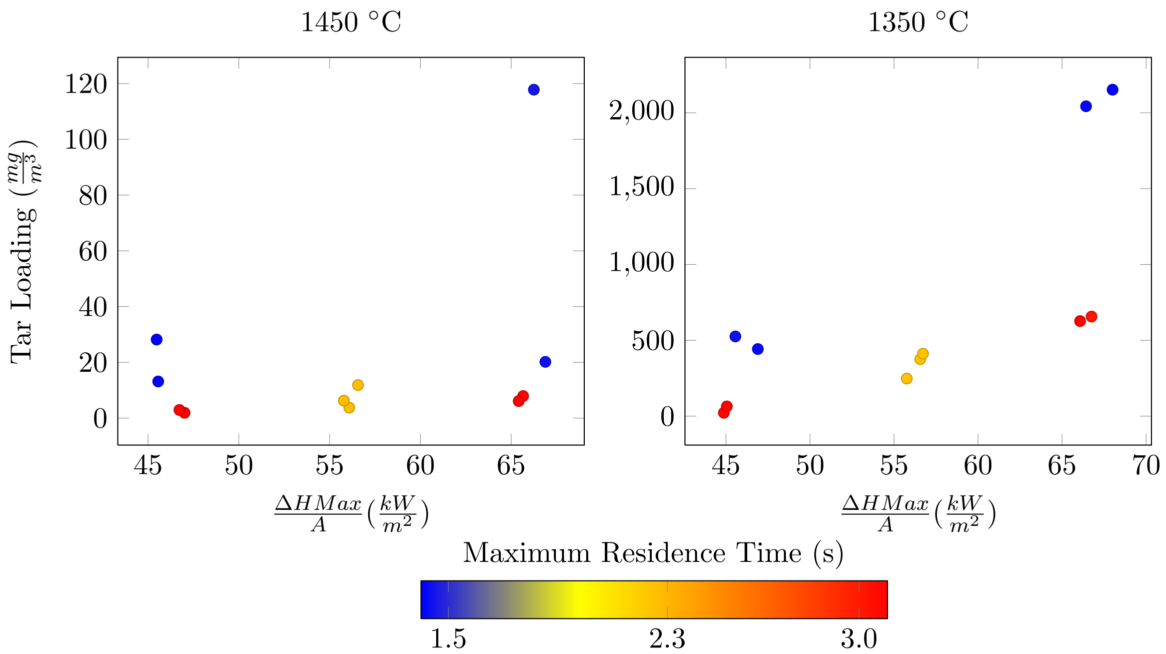

Figure 11: Blah blah blah blah SDPFOICJPFOIJD

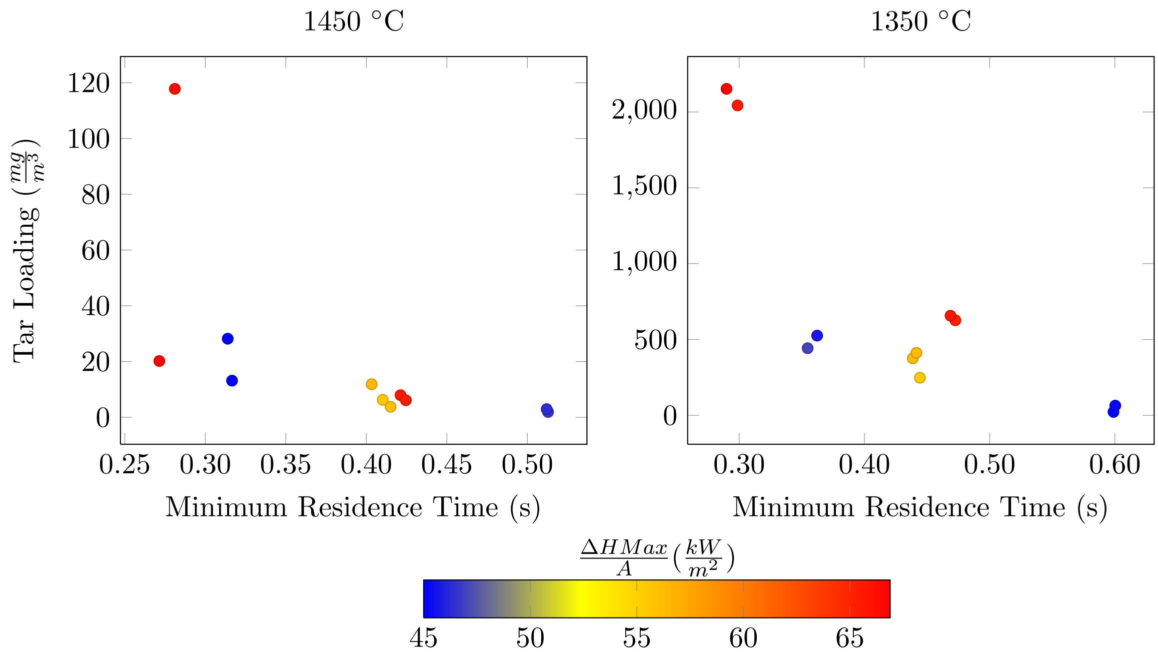

Figure 12: Blah blah blah blah SDPFOICJPFOIJD

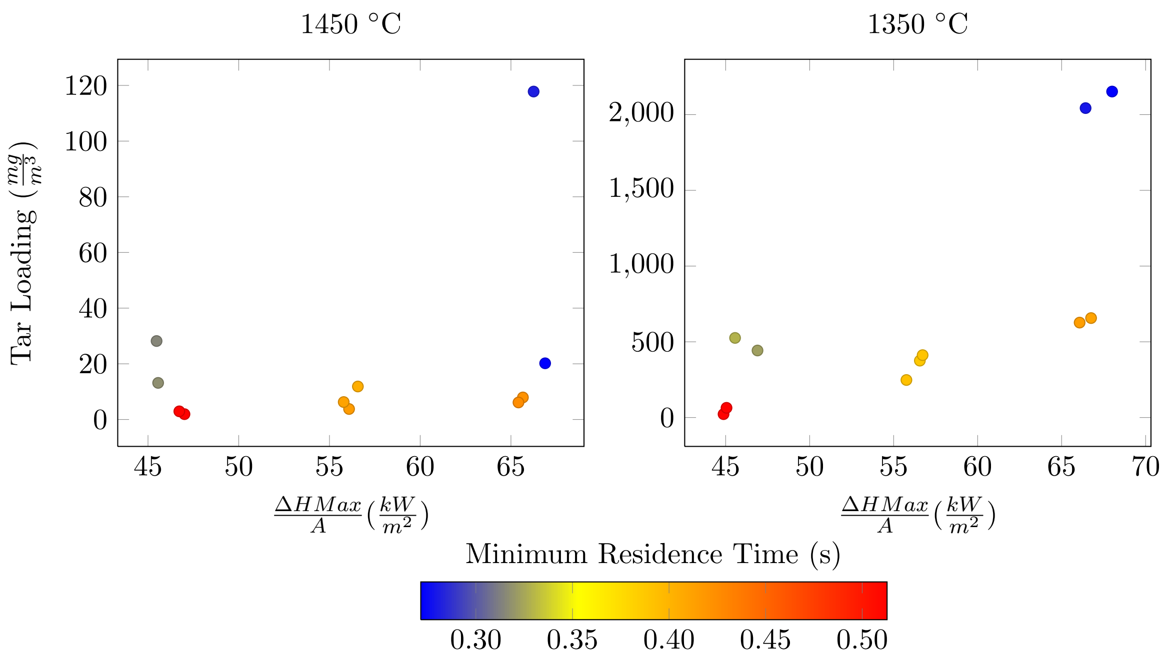

Figure 13: Blah blah blah blah SDPFOICJPFOIJD

Table 4: ANOVA results on effects of designed experimental campaign for methane yield.

Effect	Prob <F	
	1350 °C	1450 °C
$t_{res,min}$	<0.0001	0.0001
$\Delta H_{Max}/A$	<0.0001	0.0065
$t_{res,min} \times \Delta H_{Max}/A$	0.0009	0.1305

Tar Loading

Methane Yield

Conclusion

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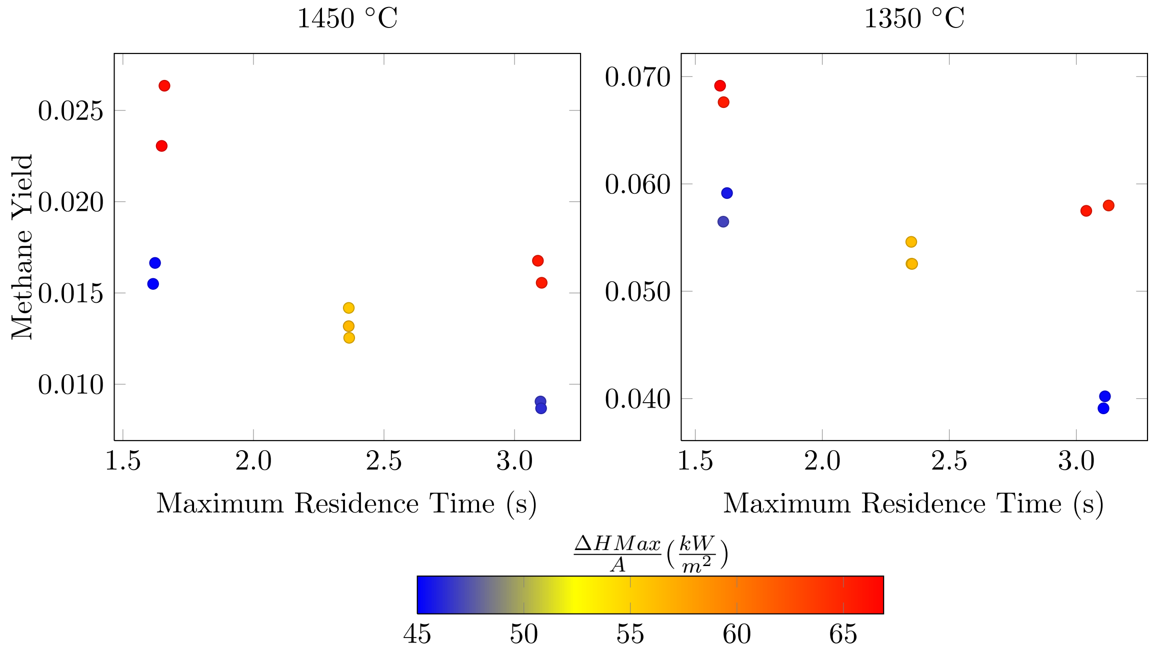

Figure 14: Blah blah blah blah SDPFOICJPFOIJD

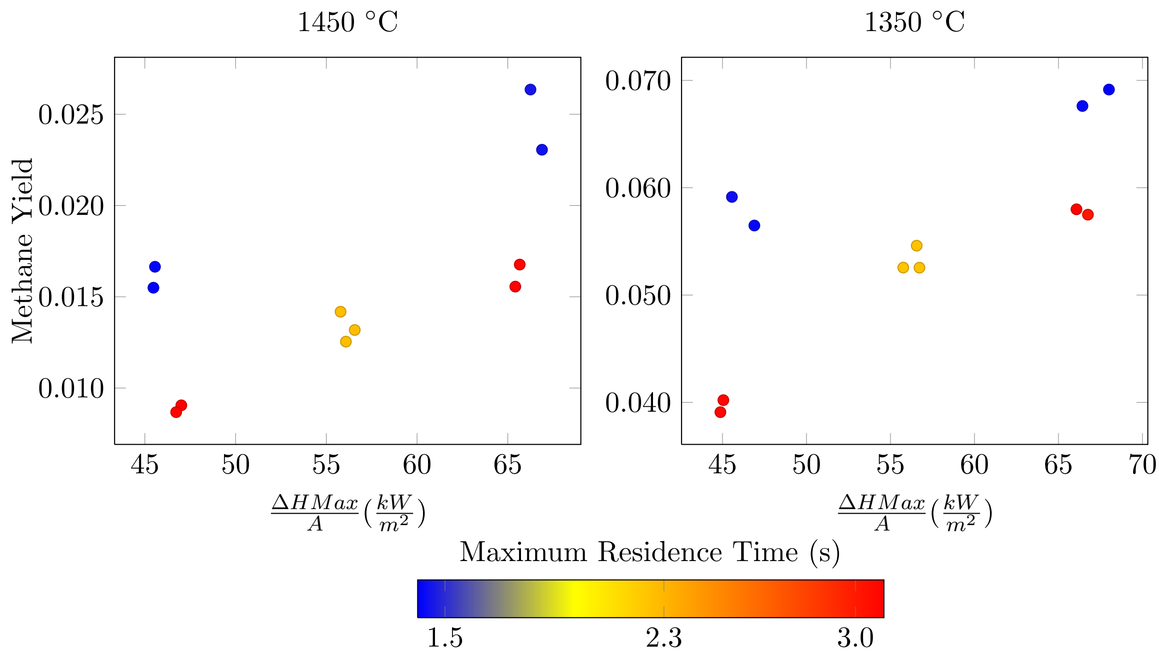

Figure 15: Blah blah blah blah SDPFOICJPFOIJD

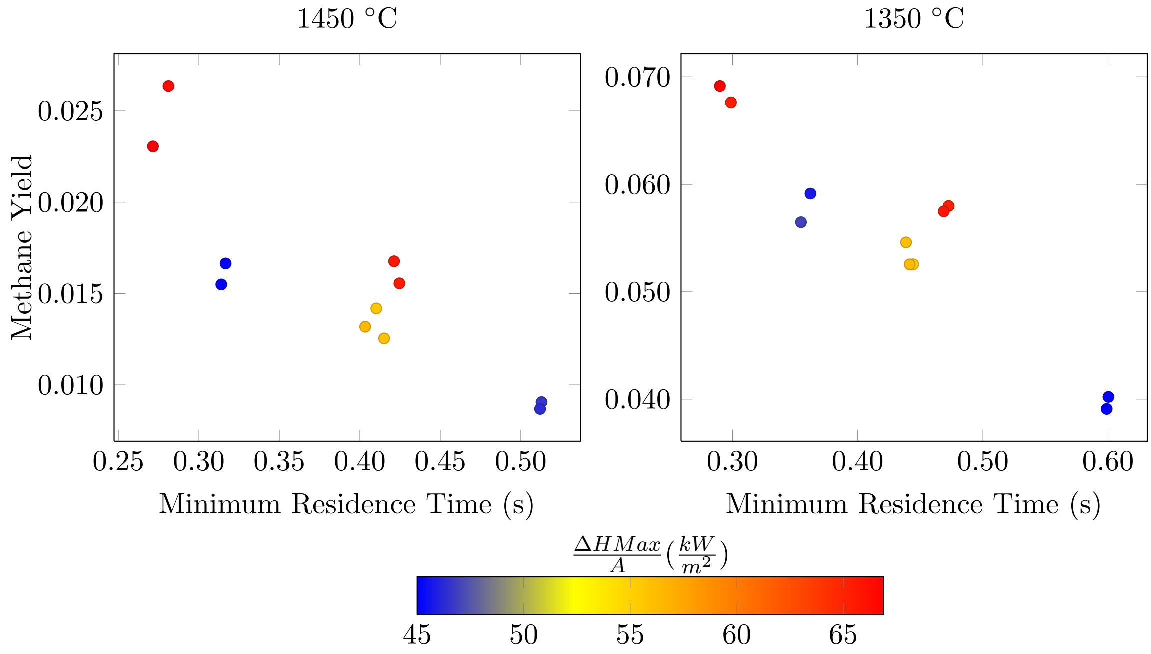

Figure 16: Blah blah blah blah SDPFOICJPFOIJD

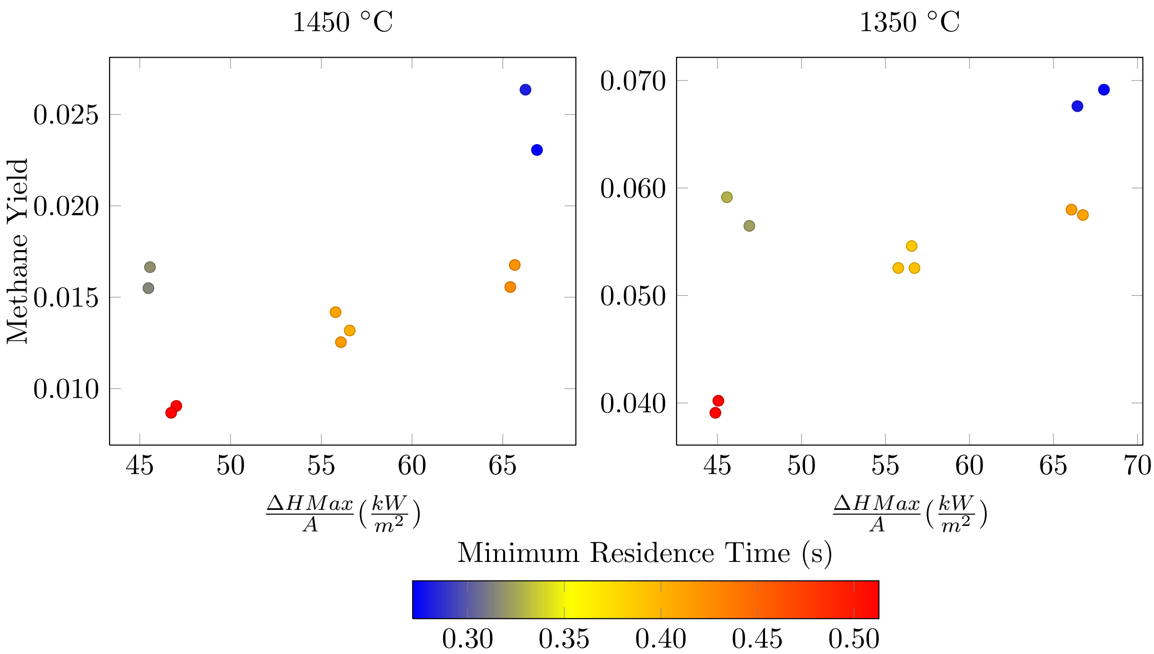

Figure 17: Blah blah blah blah SDPFOICJPFOIJD

A Experimental Set Points

Setpoints for enthalpy vs. space time experiments. Steam temperature is at 500 °C for all runs, and argon flow is 2 SLPM.

Target Max ΔH (kW)	Target Maximum Residence Time (s)	Temp. (°C)	Biomass (lb/hr)	Ent. N_2 (SLPM)	Ent. CO_2 (SLPM)	Makeup N_2 (SLPM)	Steam (g/min)	Pressure (psig)
3.3	1.6	1450	2.1	6.7	6.0	1.4	19.3	34
3.3	3.1	1450	2.2	9.3	3.8	11.1	12.0	64
4.05	2.35	1450	2.6	10.5	4.9	14.4	15.7	61
4.8	1.6	1450	3.5	14.3	6.4	0	20.3	41
4.8	3.1	1450	3.6	17.9	3.8	4.5	12.2	67
3.3	1.6	1350	2.1	6.3	6.3	7.9	20.2	40
3.3	3.1	1350	2.0	8.3	3.9	19.1	12.6	75
4.05	2.35	1350	2.8	11.6	4.9	14.5	15.8	62
4.8	1.6	1350	3.7	15.6	6.4	1	20.6	42
4.8	3.1	1350	3.8	18.9	3.9	7.0	12.5	72