CYCLONES FOR THE REMOVAL OF BIOCHAR FROM A FLUDIZED BED REACTOR

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Abstract

Gasification of cotton gin trash (CGT) has the potential to be a financially feasible means of electricity generation for cotton gins across the nation. Synthesis gas (syngas), which is a low calorific value (LCV) gas and biochar are the two products from the thermochemical gasification process. An estimated 20% of the incoming feedstock mass leaves the fluidized bed reactor as biochar to the cyclone system. The goal of the cyclone system is to remove the maximum amount of biochar prior to fueling the engine to produce electricity. The temperature of syngas and biochar leaving the gasifier is in the range of 800-1,000°F. The syngas is void of oxygen and must remain void of oxygen until it enters the generator. The goal of this research was to test the hypothesis that properly designed cyclones could separate the char from the LCV gas at 98% efficiencies with the potential of maintaining the syngas void of oxygen for proper and safe biochar removal. A laboratory scale model was constructed using six-inch barrel, TAMU 1D2D, and TAMU 1D3D cyclones. The measured performances of the cyclones at ambient temperatures were determined and reported. Results were collection efficiencies of 97% for the barrel and 1D2D cyclones, 98% for the 1D3D cyclone, and 99% for the 1D2D and 1D3D cyclones connected in series.

Introduction

The Texas A&M University's Department of Biological and Agricultural Engineering (BAEN) began their research on fluidized bed gasification in 1980. Two patents resulted: U.S. Patent Serial No. 4,848,249 (Parnell and LePori, 1990) and a new provisional patent Serial No. 61/302,001 (Capareda, Parnell, and LePori, 2010). Fluidized bed gasification is the technology of utilizing a biomass that was presumed to have little value from ginning cotton. It potentially enables a cotton gin the ability to be energy self-sufficient with a system that is both economically feasible and environmentally friendly. CGT is a low eutectic fuel that will result in significant slagging and fouling if the thermal reaction exceeds 1,400°F. This problem makes all thermal conversion systems that result in temperatures higher than the eutectic point unsustainable.

The fluidized bed gasifier minimizes slagging by maintaining the reaction temperature less than the eutectic temperature (1,400 °F) by limiting the oxygen in the gasification phase. LePori (1985) published images of the CGT ash pellets and cottonseed hull pellets, illustrating the difference between low eutectic fuels and fuels that have ash that does not melt at relatively low temperatures (figure 1).

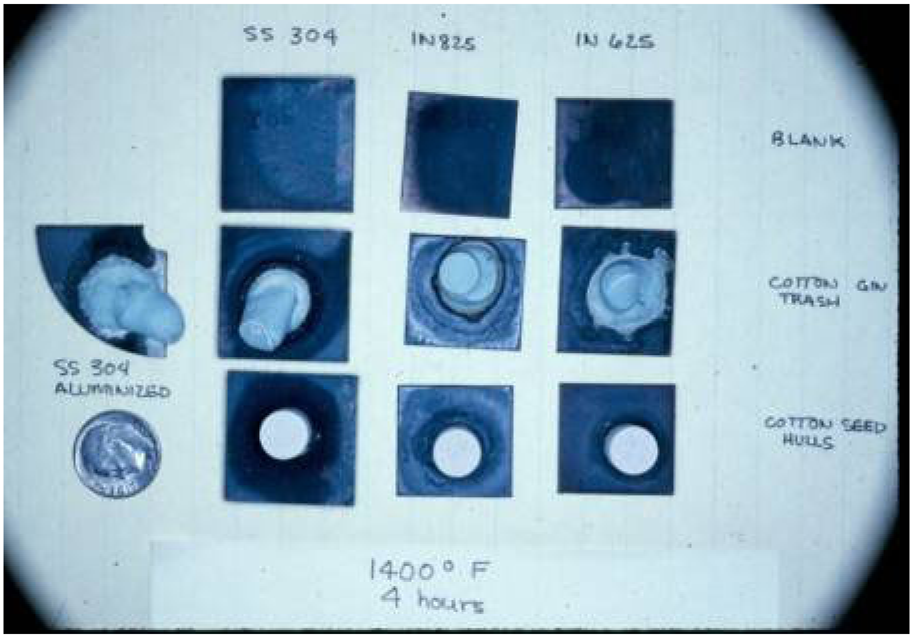

Figure 1.Results of testing pelletized CGT ash and cotton seed hull ash to determine ash melting point. The pellets were placed in an oven for four hours at 1,400 °F. The CGT ash (middle row) melted while the cotton seed hull ash did not melt. CGT is a fuel that has a low eutectic point and will be plagued with significant slagging and fouling. (LePori, 1985).

The products of gasification are synthesis gas, commonly referred to as producer gas (CO, H_2, CH_4, C_2H_6, C_2H_4), and biochar. Approximately 20% of the incoming CGT fuel leaves the gasifier as biochar. The temperature of syngas and biochar leaving the gasifier is in the range of 800-1,200°F. The goal of the cyclone system is to remove the maximum amount of biochar prior to fueling the engine to produce electricity. The syngas is void of oxygen and must remain void of oxygen until it enters the generator. It is estimated that the capital costs of electricity generation by direct fueling of the generator with syngas is $1M per Megawatt (MW). In contrast, using the syngas to produce steam and subsequently producing electricity with a steam turbine is $2M/MW. It is hypothesized that sufficient biochar can be safely separated from the syngas using properly designed cyclones while maintaining a gas void of oxygen. The performances of the cyclones in ambient air were for loadings in the range of 100-400 g/min of biochar.

Materials and Procedures

Figure 2 is an image of the testing system. The major components of the system are labeled and described. The laminar flow meter was used to measure flow rate. Flow rate was directly proportional to the pressure drop measure in inches water gage (in w.g.). Equation 1 is the laminar flow meter equation to obtain flow rate in units of cubic feet per minute (CFM):

$$Q\ (cfm) = 12.9 * \Delta P\ (in.\ w.g.) \quad (1)$$

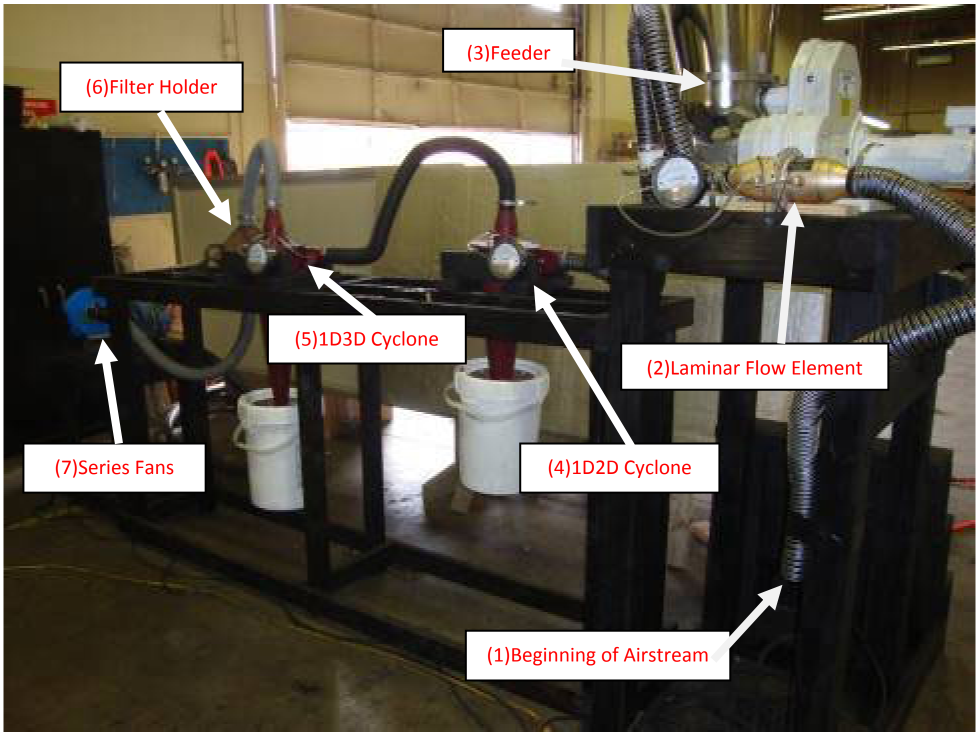

Figure 2. Experimental setup. (1) Ambient air enters the system. (2) A Laminar flow element was used to measure the flow rate (Q) of air. (3) Adjustable volumetric feeder for controlling the biochar feed rates into the airstream. (4) and (5) 1D2D and 1D3D cyclones in series with respective individual buckets to hold the biochar captured. (6) Glass fiber filter holder. (7) Two fans in series to pull air through the system. Pressure gauges were used to measure pressure drops across the cyclones.

The feeder was an adjustable volumetric feeder that controlled the mass of biochar delivered to the air stream for each test. The feeder is powered by a DC variable speed motor. Two cyclones were used for the series cyclone tests. It was hypothesized that a1D2D, low pressure cyclone would serve to remove the large PM and the 1D3D cyclone would remove most of the remaining biochar. Both cyclones were 6-inch diameter steel cyclones designed using the TAMU cyclone design method. Biochar laden air entered the 1D2D and 1D2D cyclone exhaust was conveyed to the 1D3D cyclone inlet. Finally, the exhaust of the 1D3D was passed through an 8"x10" glass fiber filter for protocol #1 tests. This filter captured PM that penetrated the series cyclone system. Air-tight, three- gallon buckets with screw top lids served as collection chambers were attached at the exits of the two cyclones. The bucket lids contain a ratcheting lock system and an internal gasket to ensure an air-tight fit. Two fans in series generated the vacuum to pull the air and biochar through the system.

<u>Char Parameters</u>

Our tests were conducted using sorghum char collected from the previous gasification experiments. Particle size distributions (PSDs) were performed with a Coulter Counter and particle densities were obtained with an air pycnometer. Figure 3 shows the measured percent volume versus natural log of the particle size and the best fit lognormal distribution. Properties of CGT and sorghum biochar are shown in table 1.

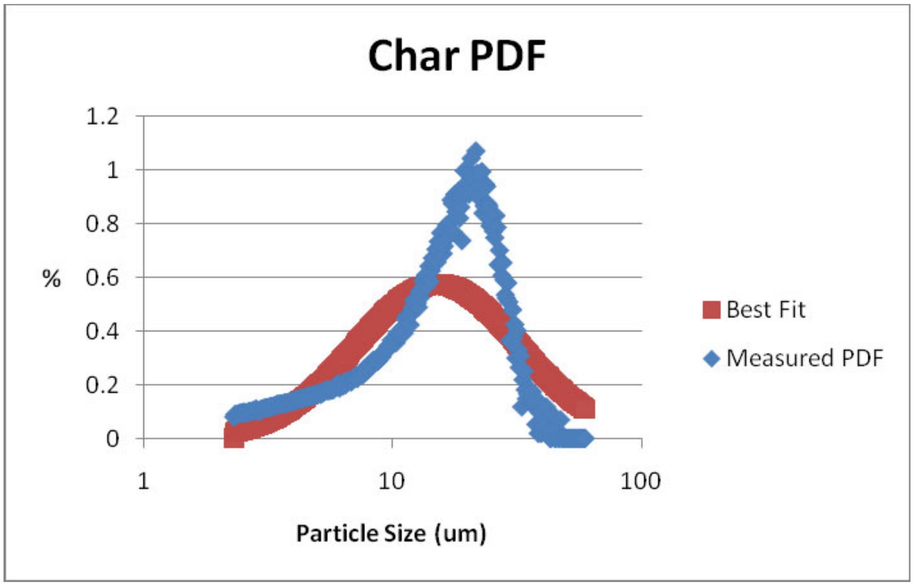

Figure 3. Probability density functions (PDF) particle size distributions (PSD) of the measured and modeled biochar particle size distributions. The PSD is a log-normal distribution.

Table 1. CGT and Sorghum biochar PSDs defined by MMDs and GSDs and measurements of % volatiles, % Ash, and % carbon of CGT from the proximate analysis. Both CGT and Sorghum biochar have similar PSDs and similar ash, carbon, and volatile contents.

Char	MMD (um)	GSD	Volatile (%)	Ash (%)	Carbon (%)
CGT	21	2.4	14.3	59.1	26.6
Sorghum	24	2.1	12.2	61.3	26.5

Protocol 1

Our first series of tests consisted of feeding 100-400 g/min of biochar to the series cyclone system followed by a glass fiber filter in the filter holder. We tested 3 replications for the 1D2D and 1D3D cyclones separately and 3 replications for the cyclones in series. The system was purged of remaining char particles prior to each run by running air through the system. The mass of char placed in the feeder hopper was measured and recorded. Testing time began as soon as the fans were turned was recorded for each run. Pressure drop across the cyclones and the laminar flow element were recorded at the beginning and end of each test. Masses of captured biochar in the collection buckets mounted to the bottom of the cyclones were measured and recorded. Upon collecting approximately 1.5 grams of biochar, the increased pressure across the glass fiber resulted in a significant reduction in flow rate through the system. This reduction in Q dropped the design flow rate through the system outside of the optimal Q range for the cyclones. The ideal inlet velocities for 1D2D and 1D3D cyclones are 2400 feet per minute (fpm) and 3200 fpm, respectively. Both cyclones have an acceptable operating range of ± 400 fpm on either side of the optimal inlet velocity. The inlet area for both cyclones is $D^2/8$. Since both cyclones are 6-inch in diameters, the inlet area for both is 0.0313 ft^2. Table 2 lists the range of acceptable air flow rates through the test system based upon the optimal and acceptable inlet velocities.

Table 2.Optimum flow rates for cyclone tests based on optimal inlet velocities (Parnell, 1996).

Cyclone	Velocity	Flow Rate
	(fpm)	*(cfm)*
1D2D		
Low	2,000	63
Optimal	2,400	75
High	2,800	88
1D3D		
Low	2,800	88
Optimal	3,200	100
High	3,600	113

Protocol 2

A second test protocol consisted of removing the glass fiber filter and exhausting the PM that penetrated the cyclone(s). The biochar capture efficiencies were determined by subtracting the measured mass captured by the measured mass of biochar delivered to the system. The entire system was flushed of any remaining char in the system prior to each test. The system was then turned on, with time being recorded for how long char was conveyed into the air stream. Pressure drops across the cyclones were measured along with the pressure drops across the laminar flow element during each test. All of the pressure drops remained consistent throughout the tests. The feeding times from start to finish were recorded. Compressed air was used to push the residual biochar particles in the feeder through the cyclones while the fans were still operating. Once all of the char was conveyed through the system, the fans were turned off and the mass of biochar collected by the cyclone(s) in the collection containers was measured. Three replications were conducted on the barrel, 1D2D, and 1D3D cyclones individually, along with the 1D2D and 1D3D cyclones in series. Once the total mass of biochar was determined for each test, the collection efficiencies were calculated using equation 2:

$$\%Efficiency = \frac{Biochar_{Captured}}{Biochar_{In}} \times 100 \qquad (2)$$

Results

Capturing the exiting concentrations of biochar with the glass fiber filters resulted in the system clogging therefore, data was analyzed from protocol 2. All of the cyclones were tested individually along with the 1D2D and 1D3D being testing in a series connection (tables 3-5). The data was compiled and an average was taken of the data and is represented in table 6.

Table 3. Six-inch diameter barrel cyclone test data and average tests results for 3 replications.

Cyclone	Barrel	Barrel	Barrel
Flow Rate (cfm)	104	104	104
Input (g)	1190	965	1020
Feed rate (g/min)	170	193	186
Feed rate (g/m^3)	57.4	65.2	62.8
Time (min)	7	5	5.5
Total Captured (g)	1150	935	992
% Efficiency	96.8	96.9	97.1
Exiting Concentration (g/min)	5.49	6.06	5.37
Exiting Concentration (g/m^3)	1.86	2.05	1.82

Table 4. Six-inch TAMU 1D2D + 1D3D test data and average test results for each cyclone for 3 replications.

Cyclone	1D2D	1D2D	1D2D	1D3D	1D3D	1D3D
Flow rate (cfm)	95	98	99	103	97	99
1D2D ΔP (in w.g.)	4.2	3.9	2.6	X	X	X
1D3D ΔP (in w.g.)	X	X	X	2.1	1.9	2.1
Time (min)	6.5	5.4	5	4.67	4.5	5.5
Input (g)	1230	905	890	874	797	937
Feed rate (g/min)	187	163	170	183	174	166
Feed rate (g/m^3)	69.2	58.6	60.3	62.6	63.4	59.0
1D2D Bucket (g)	1216	879	848	X	X	X
1D3D Bucket (g)	X	X	X	854	782	913
Total PM Captured (g)	1220	879	848	854	782	913
% Efficiency	99	97	95	98	98	97
Exiting Concentration (g/min)	1.9	4.9	8.5	4.2	3.3	4.4
Exiting Concentration (g/m^3)	0.69	1.76	3.02	1.45	1.21	1.58

Table 5. The TAMU 1D2D and 1D3D six-inch cyclones connected in series measured performances.

Cyclone	1D2D+1D3D	1D2D+1D3D	1D2D+1D2D
Flow rate (cfm)	88	101	102
1D2D ΔP (in w.g.)	4.6	3.4	3.2
1D3D ΔP (in w.g.)	3.2	3.6	3.6
Time (min)	5	7	13.5
Input (g)	2100	1180	2470
Feed rate (g/min)	414	167	179
Feed rate (g/m3)	167	58.8	62.0
1D2D Bucket (g)	2060	1170	2400
1D3D Bucket (g)	6.2	3.3	17.4
Total Captured (g)	2070	1170	2420
% Efficiency	99	99	98
Exiting Concentration (g/min)	5.5	1.2	3.7
Exiting Concentration (g/m^3)	2.23	0.41	1.30

Table 6. Averages of the data measured from the testing of the cyclone's particle collection.

Average Table				
Cyclones	1D2D+1D3D	1D3D	1D2D	Barrel
Feed rate (g/min)	253	174	172	183
Feed rate (g/m^3)	95.8	61.7	62.7	61.8
Capture Efficiency (%)	99	98	97	97
Exiting Concentration (g/min)	3.5	4.0	5.1	5.64
Exiting Concentration (g/m^3)	1.31	1.41	1.82	1.91

From table 6, the series connection of the 1D2D and 1D3D cyclone yields the highest particle capture efficiency of 99%, followed by the 1D3D, 1D2D, and the barrel cyclone, with a particle collection efficiency of 98%, 97%, and 97%, respectively. Table 6 includes the measured biochar feed rates into the system along with their exiting concentrations of biochar.

Data from table 6 displays that when using a single cyclone for the removal of the biochar, efficiencies of 97% and higher are achievable. Pressure drops associated with a single cyclone are half of that when using a series of cyclones. When an economical means of electrical generation is of top priority, minimizing the pressure drop for the entire gasification system is critical. The fan(s) that are used to fluidize the bed material of the fluidized bed gasification reactor have to operate at consistent flow in order for the proper amount of oxygen to be introduced into the system. With higher pressure drop across the cyclones, a larger amount of energy is required to operate the fan(s) that fluidize the reactor.

Operating the 1D2D and 1D3D cyclones in a series connection, a large portion of the particles (~97%) are removed by the 1D2D cyclone and a small portion (~2%) are removed by the 1D3D cyclone. Figure 4 is a photograph of the collection buckets from the 1D2D (right) and 1D3D (left) cyclones after a series test was conducted.

Figure 4. Collection buckets from the 1D3D (left) and 1D2D (right) cyclones after a test with the cyclones connected in series.

Summary

The biochar's PSD and MMD make it an ideal candidate for removal through the use of cyclones. With 40% of the biochar consisting of volatile products and carbon and temperatures in the range of 800-1,200°F, keeping the char in an oxygen-free environment is crucial to preventing fire hazards. High rates of particle capture efficiency are achieved from the use of a single cyclone. Whether the gasifier has a single barrel or 1D2D cyclone to remove the biochar from the syngas stream, capture efficiencies of 97% can be achieved. By using a single cyclone, capital cost will be reduced along with the pressure drop that would require a higher power fan to fluidize the gasification bed.

Future Research

Ambient conditions were used for testing the capture efficiency of the TAMU cyclones. Testing with a heated airstream to simulate the fluidized bed reactor temperatures will identify any effect of the decreased air density on the cyclone capture efficiencies. Improvements to the experimental setup are needed. Incorporating a rotary airlock to the volumetric feeder will reduce the amount of air pulled through the feeder; therefore, increasing the control of the biochar feed rates into the airstream. Instrumentation upgrades will be performed to increase the accuracy of the pressure drop readings across the cyclones and the laminar flow element. Cyclone modifications will be investigated to improve the biochar capture efficiency. Concentrations of biochar that escape the cyclones will be directly fed into an internal combustion engine. An experiment of the effects the exiting concentrations of biochar will have on the engine will be conducted.

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