### REDUCING PM CONCENTRATIONS IN SIMULATED HIGH TEMPERATURE GAS STREAMS D. R. Luehrs C.B. Parnell R.O. McGee Texas A&M University College Station, TX

# <u>Abstract</u>

The goal of this research is to use the energy in cotton gin trash (CGT) to fuel an internal combustion engine (ICE) driving a generator to produce electricity for a cotton gin. CGT has a low eutectic point, since CGT char melts at low temperatures. Biomasses with low eutectic points cannot be combusted because of the resulting high temperatures causing slagging and fouling. We have used fluidized bed gasification to control the reaction temperatures and capture the energy in the biomass of cotton gin trash to produce a synthetic gas (syngas) that can be fed directly into an internal combustion engine/generator (ICE) to produce electricity. The syngas is used to convey the char from the bed to the gas cleanup system consisting of specially designed cyclones. The cyclones were used to reduce particulate matter (PM) concentrations in the syngas prior to delivery to the ICE to minimize slagging and fouling. Cyclones are capable of reducing the concentrations of particulate matter from syngas streams. The temperatures of the syngas leaving the gasification bed ranges from 700 to 1400°F. These high temperatures impact the cyclone inlet velocities as a consequence of the reduced gas densities. Changes in gas densities will impact the cyclone design. It was hypothesized that the changes in cyclone performance at lower gas densities could be approximated by increasing the inlet velocities of the syngas using air at standard temperature and pressure (STP) and cyclone inlet velocities corresponding to velocities of the hot gases. Testing of cyclone performances in simulated high temperature gas streams is planned. Preliminary cyclone testing results indicate that the location of the vortex inverter in the cyclone relative to the natural length can significantly impact the cyclone performance and design. It is anticipated that testing will be conducted at inlet velocities of 3,000, 6,000 and 9,000 feet per minute (fpm). Increasing inlet velocities will result in increasing the cyclone's natural length. This study was limited to testing cyclone performances at ambient temperatures and simulating high temperature airflow rates and velocities for safety purposes. Natural lengths were used to help determine the optimum location of the vortex inverter.

# **Background**

Fluidized-bed gasification (FBG) is a proposed renewable energy solution for cotton gins as demand for electricity from the grid increases. Currently, cotton gins require 30 to 50 kilowatts (kW) to produce a bale of cotton. The faculty members in the department of Biological and Agricultural Engineering (BAEN) have been conducting research on FBG of biomasses including cotton gin trash (CGT) for a number of years. The goals of this research were to produce a synthetic gas (syngas) that could be used to produce electricity (Capareda et al. 2010; Capareda and Parnell, 2007; LePori and Parnell, 1985; Maglinao, 2013; Parnell, 1985)

FBG is a thermochemical reaction, with regulated energy loading rates and fuel to air ratios, converting a biomass into two products in the exiting gas stream: syngas and bio-char (LePori et al., 1985). Syngas comprises 80% of the mass in the gas stream and bio-char comprises the remaining 20%. CGT is a low eutectic biomass, meaning that the ash/char produced from combustion has a low melting point. Melting ash/char will result in slagging and fouling of a combustion system (LePori, et al., 1985). FBG allows for controlling the temperature to levels below those resulting in problems.

The first patent on the TAMU gasifier in 1989 (US Patent No. 4848249) and 2010 provisional patent (Serial No. 61/302,001) incorporated cyclones in series for biochar removal. The design concept was to have the first cyclone remove the large particles and the second cyclone removed the smaller particles. Saucier et al. (2008) reported that two cyclones were not needed. One cyclone removed as much as the series cyclone. There was no need for a series cyclone system. The 1D2D and 1D3D cyclones had particle capture efficiencies in excess of 95%.

FBG is one of the methods used to extract useable energy in the form of a gas from biomass. Combustion of low eutectic biomass will result in slagging and fouling. CGT contains an energy content of approximately 7,000 Btu/lb. The syngas produced can have an approximate energy content of 200 Btu per dry standard cubic foot (Btu/dscf) (Capareda et al., 2010). The bio-char laden syngas' temperature leaving the bed is 1,000 to1400°F. The syngas

temperature entering the cyclone is typically 700°F. The energy loading of the gasifier has an upper limit of 2 million Btu per square foot per hour (Btu/ft<sup>2</sup>-hr). The fuel- to- air ratio was 1.0. The bed area was 0.2 ft<sup>2</sup>.

A syngas fueled internal combustion engine (ICE) has an estimated capital cost of \$1 million per MW as opposed to \$2 million per MW for the boiler/steam turbine concept (Capareda et al. 2010). The method used to reduce concentrations of bio-char in the syngas is specially designed cyclones.

### **Introduction**

The low Btu gases from the bed through the cyclone are void of oxygen. Test cyclones will be constructed of steel capable of operating at high temperatures. The temperatures of the syngas leaving the gasification bed ranges from 700 to 1400°F. The inlet velocities of the cyclones are impacted by the reduced gas densities. Changes in gas densities will impact the cyclone design. It was hypothesized that the changes in cyclone performance could be measured by testing cyclones at STP with inlet at velocities corresponding to those associated with syngas densities.

The bio-char test concentrations in the syngas were calculated using the anticipated cyclone inlet loadings. As the temperature of the syngas increases, its density will decrease. A constant mass flow rate of syngas from the bed to the cyclone will result in an increased volumetric flow rates and associated inlet velocities of syngas from FBG bed. The inlet velocities of air at STP corresponding to the simulated high temperature gases are shown in table 1.

Table 1. Approximate inlet velocities of air at STP used to simulated inlet velocities of high temperature gases.

Related Temperature	Related Density	Inlet Velocity
(°F)	(lb/ft3)	(fpm)
70	0.075	3200
202	0.06	4000
368	0.048	5000
533	0.04	6000
699	0.0343	7000
864	0.03	8000
1030	0.0267	9000

Increased inlet velocities impact the cyclone's natural length. The term natural length describes the length the air stream travels down the vertical axis of the cyclone from the bottom of the inlet to the point where the outer vortex (strand) changes direction moving up the vertical axis. The vortex inverter in the barrel cyclone serves as a physical method of limiting the downward movement of the strands. Preliminary testing of placing a vortex inverter near the natural length of the test cyclone resulted in very high bio-char capture efficiencies in preliminary testing.

#### **Objective**

The goal of this work is to develop a cyclone capable of efficiently removing bio-char from high temperature gas streams. The objective of this research was to determine bio-char capture efficiencies for anticipated bio-char concentrations leaving a FBG reactor bed at simulated high temperatures.

### **Materials and Methods**

## **Testing System**

The objective of this research is to design and test cyclones that can reduce the concentration of bio-char from syngas at high temperatures. The questions were as follows:

- Can a properly designed cyclone effectively remove the bio-char particulate matter (PM) at high temperatures?
- Can we simulate cyclone performances of hot gases using increased inlet velocities of air at STP?
- ▶ Will results of cyclone tests using air at STP be used to determine natural length?
- Can we represent low density temperature gas flow rates with cyclone inlet velocities from 3,000 to 9,000 actual fpm?
- Can we control the bio-char feed rate to represent the expected concentrations from a 0.2 ft<sup>2</sup> bed fluidized bed gasifier with an energy loading of 2\*10<sup>6</sup> Btu/ft<sup>2</sup>-hr?
- > Can we determine the cyclone natural length for the proposed cyclones

**Models** 

Wang et al. (2002; 2006) published a model for cyclone design that incorporated natural length. This model utilized components of pressure drop. Assuming a constant slope of the outer vortex strand, the increased frictional forces can be used to estimate the number of turns and natural length of a test cyclone. The equations used in the TCD process are the accumulation of the factors that comprise the pressure drop inside of the cyclone. The total pressure drop can be calculated using equation 1.

$$\Delta P = \Delta P_e + \Delta P_k + \Delta P_o + \Delta P_f \tag{1}$$

where:

 $\Delta P_e$  = cyclone entry loss, equal to  $C_e * VP_i (C_e \approx 1)$ 

 $\Delta P_k$  = kinetic energy loss, VP<sub>i</sub> - VP<sub>o</sub>

 $\Delta P_o$  = outlet and inner vortex energy loss, equal to  $C_o * VP_o (C_o \approx 1.8)$ 

 $\Delta P_{f}$  = frictional energy loss, function of natural length

The total pressure drop and three of the components were calculated. The portion of pressure drop loss due to friction was treated as the unknown variable. The friction loss in one turn was calculated. Dividing the total pressure drop due to friction by the friction loss in one turn resulted in the number of turns (equation 2).

$$N_e = \frac{k(VP_i + VP_o) - C_e VP_i - (VP_i - VP_o) - C_o VP_o}{f \frac{L}{D_s} VP_s}$$
(2)

where:

K = constant  $VP_i = velocity \text{ pressure of the inlet}$   $VP_o = velocity \text{ pressure of the outlet}$  L = cyclone circumference  $D_s = equivalent \text{ stream diameter}$   $VP_s = velocity \text{ pressure of the stream}$ 

Equation 3 is the equation used to calculate natural length.

$$= 1.53N_e$$

(3)



 $L_N$ 

Figure 1. Visual test results used to determine the number of strands in the barrel cyclone's outer vortex used to determine natural length. These results were compared to the calculated natural length using the Wang model.

Accurate airflow to the cyclone was accomplished using an automated positive displacement compressor. The desired flow was monitored with an orifice meter. A Sutorbilt Legend Series positive displacement vacuum pump with the 3 inch diameter inlet was used. This pump could operate at 3,600 rpm under 14 psig of vacuum pressure.

An orifice meter was designed and built at Texas A&M University, to operate on a scale of 1 to 10 inches water gage (in. w.g.) for airflow from 20 to 75 cfm. Pressure drops detected by the orifice meter were recorded utilizing a Dwyer Magnesense differential pressure transmitter. Data points were collected every 10 seconds during testing.

The cyclone diameter used for testing was the diameter corresponding to the inlet velocity for the 3,200 fpm. The FBG bed in our study had a 6-inch diameter bed and was operated at a fuel-to-air (F/A) ratio of 1.0. The energy loading was a constant  $2*10^6$  Btu/ft<sup>2</sup>-hr. The airflow rate required for bed fluidization plus the mass of gas produced as a consequence of the gasification were used to determine the cyclone diameter. In our test set up, 0.8 lbs of gas from the biomass plus 1 lb. of fluidizing air results in a total gas mass of 1.8 lbs per minute. At STP, this mass rate is equivalent to 25 standard cubic feet per minute (scfm). The resulting diameter for the cyclone was 3 inches. The length of the cyclone was not limited.

The vortex inverter had a diameter of 0.9D and a height of 0.45D (Tullis et al., 1997). The vortex inverter was adjustable. This adjustable vortex inverter allowed for determining the performances of cyclones varying locations to achieve optimal efficiencies.

The bio-char came from the gasification of sweet sorghum and was the material used in previous cyclone work by Saucier et al. (2012). The bio-char was sieved to below 100 microns prior to testing. The bio-char particle size distributions (PSDs) are best defined by log-normal distributions defined by mass median diameters (MMDs) and geometric standard deviations (GSDs) (Cooper and Alley, 2011). The biochar used in this study had an MMD 34 micrometers ( $\mu$ m) aerodynamic equivalent diameter (AED) of 34  $\mu$ m and a geometric standard deviation (GSD) of 2.2.

Biochar produced from the TAMU FBG unit contained relatively large MMD when compared to common agricultural dusts such as cornstarch. Cornstarch has an MMD of 19  $\mu$ m while the biochar has an MMD of 34  $\mu$ m as shown in figure 2.



Figure 2. Particle size distributions of the bio-char used in this study. The plots illustrate the lognormal fit of the measured and theoretical particle size distributions (PSD) obtained using the Coulter Counter.





Figure 3. Cyclone testing system.

Collection efficiency of the cyclone was calculated using equation 4.

$$\eta = \frac{M_{capture}}{M_{capture} + M_{filter}} \times 100\%$$
<sup>(4)</sup>

where:

 $\eta$  = collection efficiency of the cyclone (%)  $M_{capture} = mass capture by the cyclone$  $M_{\text{filter}} = \text{mass of PM}$  collected on the filter

# **Results and Discussion**

Preliminary tests were conducted. The number of turns and natural length, for standard air, were calculated as shown in table 2.

ble 2. Calculate	ed of number of turns	and natural len
Inlet	Calculated Number	Natural
Velocity	of Turns	Length
(fpm)	(Ne)	(in.)
3200	5.1	7.8
4000	5.4	8.3
5000	5.7	8.7
6000	6.4	9.8
7000	6.4	9.8
8000	6.4	9.8
9000	6.4	9.8

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-	Inlet	Calculated	Measured	
	Velocity	Natural Length	Natural Length	
	(fpm)	(in)	(in)	
-	3,200	7.8	7.5	
	4,000	8.3	7.5	
	5,000	8.7	7.8	
	6,000	9.8	8.0	
	7,000	9.8	8.7	
	8,000	9.8	8.7	
	9,000	9.8	10.0	

Table 3 shows a comparison of the calculated natural length with the measured natural length.

The preliminary tests indicated that vortex inverter placement relative to the inlet is important. Over a range of inlet velocities and feed rates, the vortex inverter was adjusted to different locations relative to the inlet of the cyclone. There were significant increases in capture efficiencies as a function of vortex placement (Figure 4).



Figure 4. Capture efficiency changes with vortex inverter placement. Filter on left had a vortex inverter placement at estimated natural length. Filters on the right had vortex inverter placement below the natural length estimate.

The results of the 1D and 2D vortex inverter placement were all above 99% efficiency as shown in figure 5.



Figure 5. Vortex inverter placement results in terms of percent captured by the cyclone. The vortex inverter location A placement was with natural length of 11.5 inches. The vortex inverter location B placement was with natural length of 7.5 inches.

#### Summary

Further work needs to be conducted to determine the optimal placement of the vortex inverter as well as study the outcomes with increases of inlet velocities. Initial tests have shown that cyclones can be highly efficient at reducing bio-char concentrations.

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