EVALUATING TUBE CYCLONE PERFORMANCE FOR BIOCHAR CAPTURE

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Abstract

Fluidized bed gasification is a thermo-chemical process that converts a biomass into combustible gases (syngas). The syngas produced can be injected into an internal combustion engine (ICE) to power a generator to generate electricity. Cotton gin trash (CGT) is a biomass that has an energy content of approximately 7000 Btu per pound. By converting the energy from the CGT to electricity through gasification, cotton gins have the potential to be self-sufficient. A byproduct of the gasification process is biochar, which must be separated from the syngas before combustion in the ICE. A tube cyclone was evaluated to determine the capture efficiency of the biochar at ambient conditions. The vortex inverter position and flow rate were two factors that were analyzed to determine the effect on capture efficiency. Capture efficiency results ranged between 95 and 99%. From the results, a capture efficiency of approximately 95% can be expected when capturing biochar from the gasification process.

Background

Biomass combustion systems have been used to generate steam to power a turbine, but these systems result in slagging and fouling. The combustion process operates at a temperature much higher than the eutectic point of the ash, which causes the ash to melt and stick to the surfaces of the system. As a result, the system becomes unsustainable. To minimize slagging and fouling, fluidized bed gasification (FBG) is proposed. FBG typically operates at temperatures of approximately 1200 °F in an oxygen deprived environment. Although several types of gasification exist, FBG is a much more continuous and sustainable process.

Lepori (1985) and Maglinao (2013) have conducted research at Texas A&M University on gasification. A wide variety of feed stocks have been analyzed in the gasification process, which include cotton gin trash (CGT), woodchips, sorghum, and animal manure. Gasification is a thermo-chemical process that converts a biomass into a combustible synthesis gas (syngas). The syngas can be fed into an internal combustion engine (ICE) to generate electricity. A power requirements analysis was performed (fig. 1) to determine the potential amount of electricity that can be produced at a cotton gin.

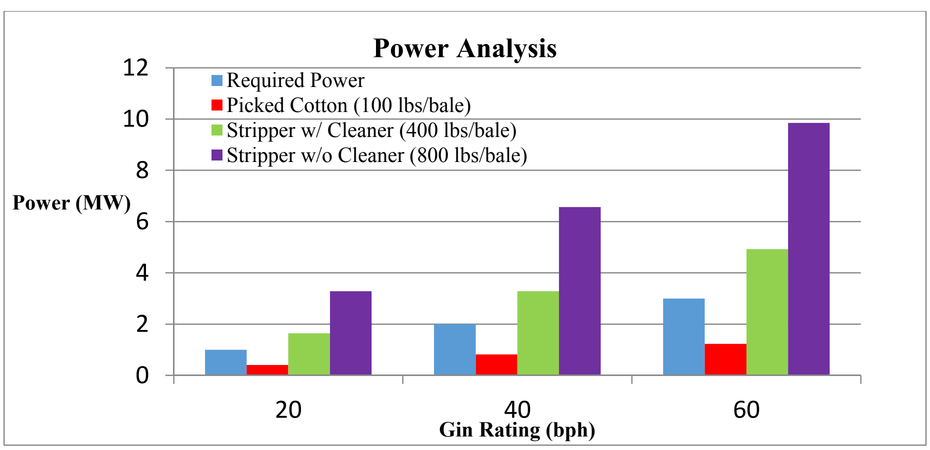

Figure 1. Analysis of power generation utilizing cotton gin trash. Stripper gins will have more than enough gin trash to exceed the gin's electricity requirements, while picker gins will only be partially self-sustaining.

Surveyed data from the Texas Cotton Ginning Association's website revealed an average usage of 50 kW-hr per bale to gin cotton (Texas Cotton Ginners Ass., 2006). This value was used to calculate the power required to operate a gin based on the gin rating. The CGT coming to the gin has an energy content of approximately 7000 Btu per pound. The amount of gin trash coming to the gin was analyzed based upon type of harvest; picked cotton, stripper with a cleaner, and stripper without a cleaner contained 100, 400, and 800 pounds of gin trash, respectively. A conservative assumption was made that 10% of the energy in the gin trash can be converted to electricity. The results of the power analysis revealed that stripped cotton has sufficient gin trash that can exceed the gin's power requirement.

The objective of the overall project is to develop engineering properties on a pilot-scale gasifier that maximizes the energy content in the syngas utilizing CGT as the fuel. The gasifier will then be scaled up to generate 500 kW of electricity.

Introduction

A byproduct of the gasification process is biochar. Biochar is an ash-like particulate discovered to be activated carbon (Capareda, 1990). Approximately 20% of the input feed is converted to biochar. An important aspect in the gasification process is the removal of biochar from the syngas. The biochar concentration in the syngas stream needs to be reduced before the gas is combusted in an ICE to be sustainable (Maglinao, 2013). Typical gasification systems utilize cyclones to separate the biochar from the syngas (Lepori et al, 1985). Cyclones are excellent particle abatement devices that are capable of achieving 90% and above capture efficiency. In addition, cyclones are relatively inexpensive to manufacture, have very few maintenance requirements, and have low operation costs (Cooper and Alley, 2011, pp. 136).

A gas containing the particulate enters the inlet of the cyclone (fig. 2) tangentially to the barrel of the cyclone. The gas stream spirals downward in the cyclone (outer vortex) using centrifugal forces to move the particles to the surface of the cyclone, where the particles will slide down and be captured. At the natural length of the cyclone near the bottom of the conical section, the outer vortex changes direction and gets inverted to the inner vortex. The inner vortex then travels upward through the center of the cyclone to the outlet.

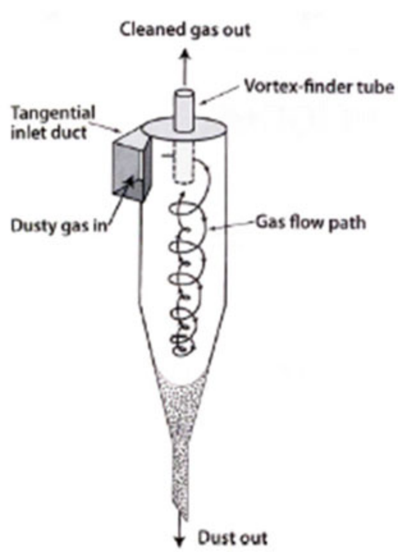

Figure 2. Cyclone Operation

Common types of cyclones used in process flow systems are 1D3D cyclones. The Ds refer to the diameter of the cyclone barrel. For a 1D3D cyclone, the "1D" designates the length of the barrel section, whereas the "3D" refers to the length of the conical section of the cyclone. A visual representation can be seen in figure 3 (Faulkner et. al., 2008).

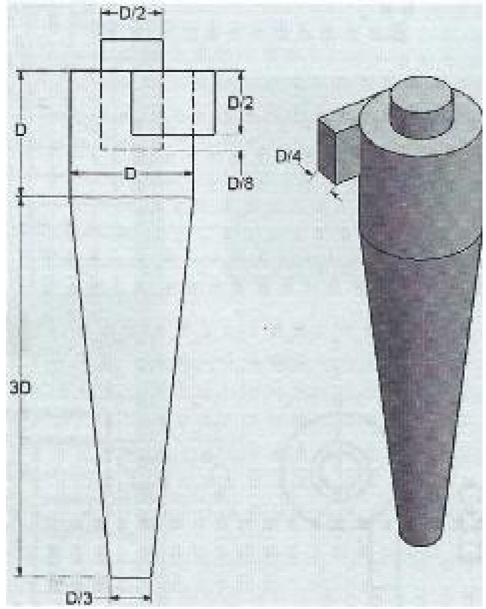

Figure 3. 1D3D Cyclone Visual Representation

Although the 1D3D cyclone is a common cyclone, there exist potential issues when using this cyclone for gasification systems. The 1D3D cyclone operates at an optimal range of inlet velocities of 3200 +/- 400 feet per minute. The 1D3D cyclone can be designed accordingly to fit this criterion. In the gasification process, however, the flow rate of the gas stream has variation that could result in an inlet velocity outside of these bounds. Simpson (1996) reported that at higher inlet velocities greater than 3200 feet per minute, the collection efficiency of the cyclone decreases.

For the current research project, a tube cyclone will be used to capture the biochar from the syngas. The tube cyclone (fig. 4) is a newly designed cyclone that is expected to handle the variation of flow rates from the gasification process. The tube cyclone is similar to a 1D3D cyclone with regards to the inlet and outlet dimensions. The difference is that the tube cyclone does not have a conical bottom section that inverts the outer vortex to the inner vortex. Instead, a vortex inverter (fig. 5) is placed within the tube cyclone to invert the outer vortex.

Figure 4. Tube cyclone

Figure 5. Vortex inverter

Research has been conducted at Texas A&M with tube cyclones. Luehrs (2014) tested the performance of a Plexiglass tube cyclone at vortex inverter positions of 4D, 6D, and 8D at ambient conditions. Each vortex inverter position correlated to a particular inlet velocity. At vortex inverter positions of 4D, 6D, and 8D, an inlet velocity of 3000, 6000, and 9000 feet per minute were used, respectively. The inlet velocities used correlated to the elevated temperatures of gases from gasification. Luehrs reported capture efficiencies of the tube cyclone at approximately 97%. In addition, Luehrs concluded that the vortex inverter should be placed below the natural length to achieve the high capture efficiency.

Objective

The objectives of the study are to:

1. Evaluate tube cyclone performance by varying flow rate and vortex inverter position.
2. Determine the optimal location of the vortex inverter in the tube cyclone to achieve maximum capture efficiency.

Materials and Methods

The tube cyclone was designed using the TAMU method for a 1D3D cyclone. Preliminary calculations (Luehrs, 2014) revealed an estimated flow rate of 25 cfm of gases from the gasification process. With a design inlet velocity of 3200 feet per minute, the inlet area of the cyclone was calculated by dividing the flow rate by the inlet velocity. The inlet area was then used to calculate the diameter of the cyclone, seen in Equation (1):

$$A_{inlet} = \frac{D^2}{8} \quad (1)$$

where
A_{inlet} = inlet area (ft^2)
D = diameter of cyclone (ft).

Equation (1) is derived from the length and width of the 1D3D cyclone inlet (fig. 3), which are D/2 and D/4, respectively. The diameter of the tube cyclone was calculated to be 3 inches, which was then used to determine the inlet and outlet dimensions. The length of the tube cyclone was sized to be 36 inches to allow sufficient variation in the vortex inverter position when testing cyclone performance. The vortex inverter is a cone with a base diameter of 2.70 inches. With this diameter, a gap of 0.15 inches between the cyclone surface and the vortex inverter allows the particles to slide below the vortex inverter while operating the cyclone. All parts of the cyclone were constructed of stainless steel by Lummus Corp. to withstand the elevated temperatures of gasification.

Biochar is the particulate material used when testing the performance of the tube cyclone. The particle size distributions (PSDs) of the input and captured biochar were obtained with a Coulter Counter (Beckman Multisizer 3). The analysis determined the best fit mass mean diameter (MMD) and geometric standard deviation (GSD) of the biochar samples. The MMD of the biochar sample will be converted from equivalent spherical diameter (ESD) to aerodynamic equivalent diameter (AED). The particles that were analyzed were between 1 and 100 µm due to Coulter Counter limitations.

Air was supplied by a positive displacement compressor (Sutobilt Corp., Type L) which served as the blower. An orifice meter was placed in the pipe immediately after the blower to measure the flow rate of ambient air entering the system. An orifice meter is a device based on Bernoulli's principle that restricts the air flow in the pipe and causes a pressure drop across the orifice. The pressure drop, along with the density of the air, correlates to the flow rate of the air in the pipe and can be characterized by Equation (2):

$$Q = 5.976 * K * {D_o}^2 * \sqrt{\frac{\Delta P}{\rho_{ma}}} \quad (2)$$

where
Q = air flow rate (acfm)
K = orifice meter constant (unit less)
D_o = diameter of the orifice (inches)
ΔP = pressure drop across orifice (inches of H_2O)
ρ_{ma} = density of moist air (lb/ft^3)

When running experiments, the pressure drop across the orifice meter was measured with a magnehelic pressure gauge (Dwyer Instruments, Inc., Model 2050). The “K” value for the orifice meter was obtained from calibration tests with a laminar flow element, and was calculated to be 0.66. The relative humidity, barometric pressure, and temperature of the air were obtained by a weather station (Ambient Weather, WS-1171A), and were used in the calculation of the density.

The feeding of the biochar was achieved by using a feed hopper and a variable speed rotary air lock apparatus. A 2 inch diameter plastic smooth wall hose was used to connect the T-section to the inlet of the cyclone. Figure 6 shows a schematic of the system that was used to evaluate the performance of the cyclone.

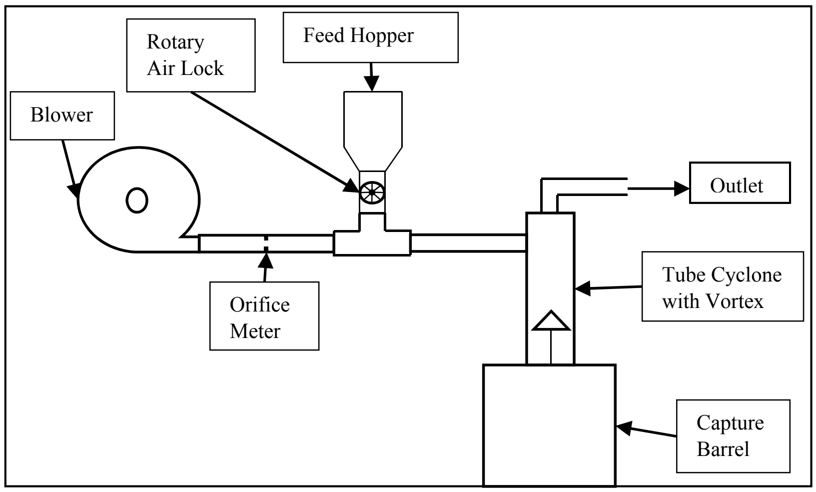

Figure 6. Tube cyclone performance set up

Cyclone performance was evaluated by determining capture efficiency. This was done by calculating the ratio of captured biochar to input biochar by mass. The masses were recorded with a digital scale (Doran Scales, Inc., PC-400), which has a maximum capacity of 1000 grams. The capture barrel weighs 300 grams. Therefore, for each run, an input of 600 grams of biochar was fed into the feed hopper. At the end of each run, the captured biochar was weighed and recorded. To ensure that all of the biochar had been run through the cyclone, the system was flushed with high flow rates of air after each run. The biochar captured after the system had been flushed was recorded and deducted from the input mass.

The performance of the cyclone was evaluated using air at ambient conditions. The vortex inverter position was varied between each test run at positions of 4D, 6D, 8D, and 10D. Each position is an increment of cyclone diameter that was measured from the bottom of the inlet of the cyclone to the base of the vortex inverter (fig. 7). For example, for a vortex inverter position of 4D, the vortex inverter was placed 12 inches below the cyclone inlet.

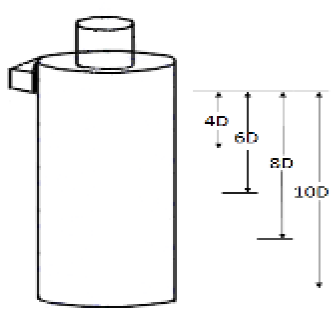

Figure 7. Vortex inverter positions within tube cyclone (not to scale)

For each vortex inverter position, two flow rates of 35 and 50 cfm at ambient conditions were used when testing the performance of the cyclone. The flow rates of 35 and 50 cfm equate to a cyclone inlet velocity of 4500 and 6400 feet per minute, respectively. Preliminary tests have shown that a flow rate of 25 cfm of ambient air was not sufficient to convey all of the biochar from the T-section to the cyclone. Observed from past data from the pilot-scale gasifier, a typical average flow rate of 35 cfm at approximately 800 ºF was recorded. The assumption was made that the temperature of gas conveying particulate does not affect the performance of the cyclone.
Two replicates were performed for each vortex inverter placement and flow rate. The response of each test run was the capture efficiency of the cyclone.

Results

The PSD of the biochar obtained from the Coulter Counter (Beckman Multisizer 3) revealed a best fit MMD of 24 µm (AED) with a GSD of 1.8 (fig. 8).

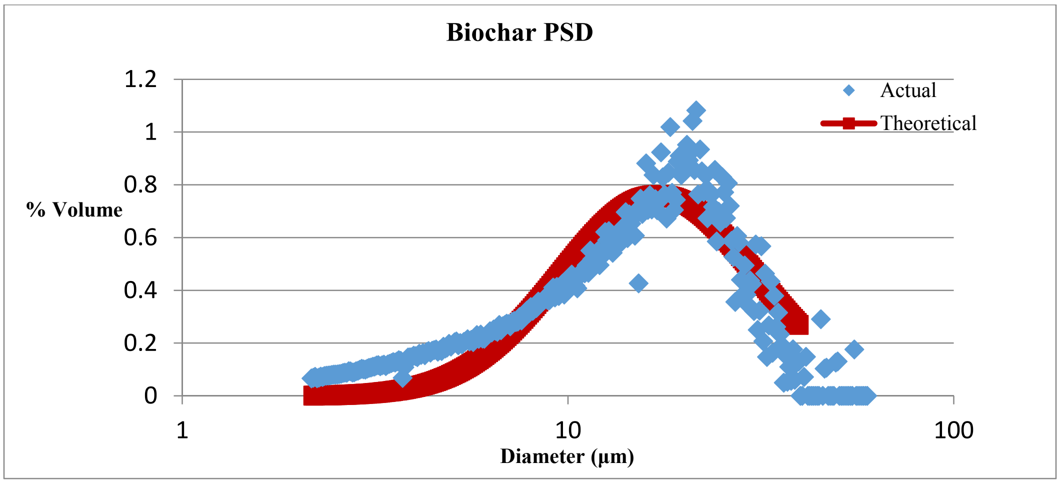

Figure 8. Biochar sample PSD with an MMD of 24 µm (AED) and GSD of 1.8.

A total of 16 experiments were run to determine the capture efficiency of the tube cyclone by varying flow rate and vortex inverter position (table 1). Each run had a testing time of approximately 6 minutes. The average concentration of biochar for flow rates of 35 and 50 cfm were approximately 100 and 70 g/m^3, respectively.

Table 1: Tube cyclone collection efficiencies by varying flow rate and vortex inverter position.

	Flow Rate, cfm			
Vortex Inverter Position	**35**		**50**	
4D	97.7%	95.8%	97.5%	99.1%
6D	95.5%	96.6%	97.6%	97.7%
8D	98.2%	97.6%	98.1%	98.5%
10D	95.0%	97.1%	97.5%	96.4%

The capture efficiencies of the cyclone ranged between 95.0 and 99.1%. A visual representation (fig. 9) reveals a near horizontal relationship between vortex inverter position, flow rate, and capture efficiency of the tube cyclone. This horizontal relationship signifies that vortex inverter positions between 4D and 10D, and flow rates between 35 and 50 cfm, have little effect on the capture efficiency.

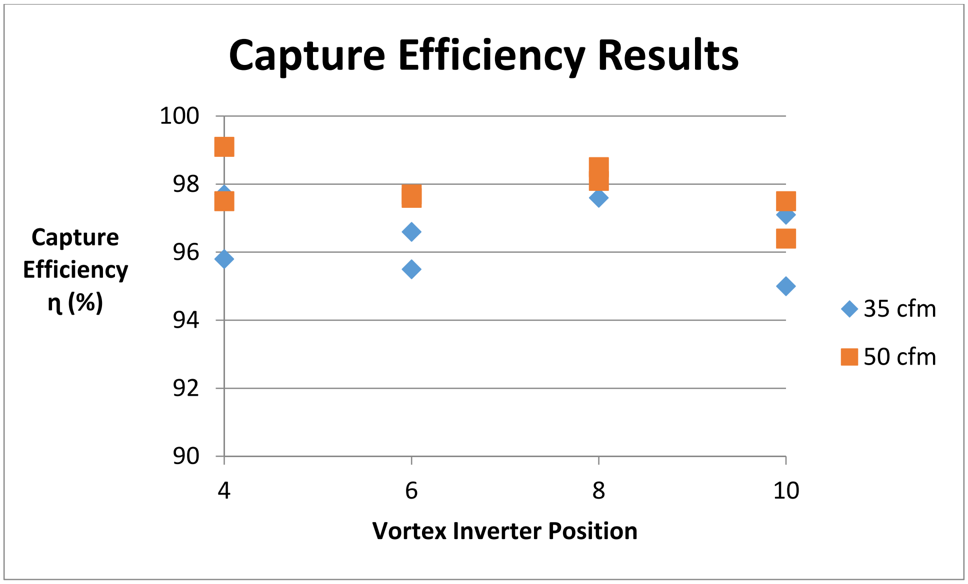

Figure 9. Plot of capture efficiency results from tube cyclone.

Summary

Fluidized bed gasification has the potential to supply cotton gins with sustainable energy by using CGT as the fuel. The concentration of biochar from the gasification process needs to be reduced from the syngas before the syngas is combusted in an ICE to maintain sustainability. The performance of a tube cyclone was analyzed by varying the vortex inverter position and the flow rate of air at ambient conditions. Biochar from previous gasification tests was used as the particulate. The capture efficiencies of the tube cyclone ranged between 95 and 99%. The results from this study indicate that the natural length of the cyclone is at the location of the vortex inverter. The capture efficiencies of the tube cyclone revealed promising results for the overall project. Approximately 95% capture efficiency of the biochar during gasification is expected.

Future work to further understand how the tube cyclone operates will need to be done. One approach is to evaluate cyclone performance by decreasing the position of the vortex inverter to 2D and 1D, perhaps. The data obtained from these tests may reveal if there exists a minimum vortex inverter position. Another aspect would be to test at lower and higher flow rates. This would allow more variation between flow rates when determining if flow rate affects capture efficiency. Finally, cyclone loading is a factor that affects the performance of a cyclone. For the tests that were run, cyclone loading remained fairly constant of each flow rate. Tests should be run that vary the cyclone loading to determine the effect on capture efficiency of the tube cyclone.

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