TEXAS A&M CYCLONE DESIGN FOR HIGH TEMPERATURE GAS STREAMS

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Abstract

Cyclones have been used for inertial separation of large particulate matter (PM) in multiple applications for many years. Texas cotton gins meet permit requirements with the use of 1D3D cyclones as Best Available Control Technology (BACT) due to the high efficiencies achieved. The Texas A&M Cyclone Design (TCD) method determines the size of cyclones at standard temperature and pressure (STP) and calculates pressure drop at actual conditions. The high efficiency of cyclones designed using the TCD method are verified by lab results and field applications. However, cyclones designed using this method have not been tested at operating conditions exceeding normal ambient temperatures. When used in gasification and engine exhaust applications, it is uncertain that cyclones will achieve the expected calculated efficiencies of the TCD method. Data from tests at normal ambient conditions can be used to construct a cyclone testing system that can evaluate cyclone performance at higher temperatures. Consequently, cyclone performance at high temperatures will be tested to validate or modify the design parameters using the TCD method. The effects of higher temperatures on air density, viscosity, cyclone size, cut point, and pressure drop will be tested and evaluated to determine the relationship between gas temperature and cyclone performance.

Introduction

The objective of this research is to study the Texas A&M University Cyclone Design (TCD) for the removal of particulate matter (PM), such as biochar, from a low-calorific-value synthesis gas (syngas) coming from a fluidized-bed gasifier being fed cotton gin trash (CGT). After cleaning, syngas can then be used as an on-site power source at a cotton gin. The United States had 682 cotton gins producing 15.2 million bales of cotton in 2011 (USDA-NASS, 2012). A survey of cotton gins' showed the average energy required to gin a bale of cotton is 50 kWh per bale (Texas Cotton Ginners Association, 2006). Texas A&M University's Biological and Agricultural Engineering has developed means to meet the energy demand of cotton gins by the process of gasification (Capareda et al., 2010). The gasification of CGT, in a fluidized-bed gasifier, enables on-site power generation for cotton gins to become energy self-sufficient. Gasification of CGT results in the production of syngas and bio-char in the gasifier gas stream. Cyclones remove the biochar from the syngas prior to fueling a generator.

Materials and Procedures

Fluidized-bed gasification is a continuous thermo-chemical conversion process in an oxygen-deprived system (Figure 1). Unlike combustion, where biomass is converted into heat, the objective in gasification is to produce syngas. This is possible by regulating the fuel-to-air ratio to maximize syngas production and keeping the reaction temperature between 700 to 900°C to prevent combustion (LePori, 1985). The char-laden syngas leaves the gasifier at temperatures around 1,000 °F. Cyclones are used to separate the bio-char from the syngas. Clean syngas can be used to fuel a generator and power the gin, while, bio-char can be spread in a field or sold as activated carbon. It is important that the syngas remains in an oxygen free environment to prevent auto-combustion of the hot gases.

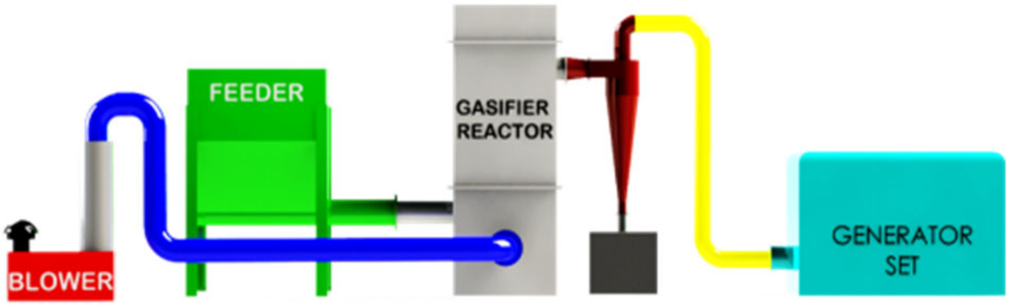

Figure 1. Texas A&M fluidized-bed gasifier design.

Like other biomass, CGT has an energy content of 7,000 Btu/pound. Current gasification methods convert 10% of the available CGT energy into syngas with an energy content of 200 Btu per dry standard cubic foot. Depending on the method used to harvest cotton from the field, either stripping or picking, the amount of CGT produced per bale will vary. A stripper without a field cleaner will typically produce 800 pounds of CGT per bale, while a stripper with a field cleaner produces 400 pounds of CGT per bale, and picked cotton averages 150 pounds of CGT per bale (Multer et al., 2010). Using the Texas Cotton Ginners average energy use of 50 kWh per bale would require 244 pounds of CGT per bale to produce enough fuel from a gasifier (Texas Cotton Ginners Association, 2006).

The TCD process finds the diameter of the barrel of a cyclone (D), using a predetermined design velocity and the air flow of the gas stream at standard conditions. Once the diameter of the cyclone has been determined, the rest of the dimensions can be found. The length of the barrel and cone will identify the cyclone and the physical length of the syngas gas stream. The width of the inlet and diameter of the outlet are used in calculating cyclone performance.

For theoretical calculations, a prototypical 6-inch cylindrical gasifier bed was chosen with an energy use of two million Btu per square foot per hour. Unit conversions (Equation 1) show that a feed rate of one pound of CGT per minute would be required and produce a mass flow rate of 2.4 pounds of gas per minute in the syngas stream. These parameters were used to design a cyclone and calculate the cyclone performance. With a mass flow rate of 2.4 pounds of gas exiting the gasifier, and using TCD at standard temperature and pressure, a 3.5 inch diameter 1D3D cyclone would be selected for cleaning the syngas. At standard conditions, a density of 0.075 lb of syngas per cubic foot results an air flow of 33 standard cubic feet per minute (CFM). At actual conditions, syngas leaves the gasifier at 1,000°F, and has a density of 0.027 lb per cubic foot and a gas flow of 92 actual CFM. This higher flow rate will produce an inlet velocity calculated at 8,800 feet per minute (fpm) for a 1D3D cyclone, which is 2.75 times higher than the designed inlet velocity for this cyclone. Previous research (Simpson and Parnell, 1995) has shown that velocity higher than 3,600 resulted in reduced collection efficiency. Calculations for the mass flow rate of the gas stream:

$$\frac{2\times 10^{6} Btu}{ft^2 - hr} \times 0.2\, ft^2 \times \frac{hr}{60\, min} = \frac{6{,}700\, Btu}{min}$$

$$\frac{6{,}700\, Btu}{min} \times \frac{lb\ of\ CGT}{7{,}000\, Btu} = \frac{0.98\, lb\ of\ CGT}{min} \tag{1}$$

$$\frac{0.98\, lb\ of\ CGT}{min} \times \frac{80\%\ syngas}{lb\ of\ CGT} = \frac{0.78\, lb\ of\ syngas}{min}$$

$$\frac{0.78\, lb\ of\ syngas}{min} + \frac{1.6\, lb\ of\ air}{min} = \frac{2.4\, lb\ of\ gas}{min}$$

Using the TCD process, the cyclone performance can be calculated for this theoretical system. Cyclone performance is based on collection efficiency and pressure drop. Collection efficiency uses the TCD cut point equation (Equation 2) to solve for the diameter of particles collected (d_{pc}) with 50% efficiency from the gas stream (Wang et al. 2002).

This cut point is used to find the lognormal distribution that represents the fractional efficiency curve of particles collected.

$$d_{pc} = \frac{1}{2}\sqrt{\frac{9\mu W}{\pi N_e V_i \rho_p}} \tag{2}$$

where:

d_{pc} = cut point (µm)
μ = gas viscosity (lb_m/ft-sec)
W = width of inlet (ft)
N_e = number of turns in cyclone
V_i = inlet velocity (ft/sec)
ρ_p = particle density (lb_m/ft^3).

The pressure drop through a cyclone is calculated using the velocity at operating temperatures and the cyclone specific constant K (Equation 5). Using the same parameters of temperature and inlet velocity the cyclone pressure drop can be calculated. The inlet velocity at 1,000 °F would be used for finding the velocity pressure of the inlet (Equation 3) and to calculate the velocity pressure of the outlet (Equation 4).

$$VP_i = \left(\frac{V_i}{1097}\right)^2 \rho_{air} \tag{3}$$

where:

VP_i = inlet velocity pressure (in. w.g.)
V_i = inlet velocity (fpm)
ρ_{air} = density of gases (lb/ft^3).

$$VP_o = \left(\frac{V_o}{1097}\right)^2 \rho_{air} \tag{4}$$

where:

VP_o = outlet velocity pressure (in. w.g.)
V_o = outlet velocity; 1D3D, $2V_i/\pi$ (fpm)
2D2D, $2V_i/\pi$ (fpm)
1D2D, $1.28V_i/\pi$ (fpm)

$$\Delta P = K(VP_i + VP_o) \tag{5}$$

where:

ΔP = pressure drop (in.w.g)
K = constant; 1D3D, 5.1
2D2D, 4.7
1D2D, 3.4

Results

The results of the calculations showed that the inlet velocity of the cyclone would increase 2-3 times when comparing the actual operating conditions to standard conditions (Table 1). It is unknown how the increase in velocity will influence the number of turns in a cyclone. The strands inside the cyclone maybe be compressed thus causing a vacuum in the collection hopper at the base of the cyclone.

Table 1. Calculated Texas A&M Cyclone Design inlet velocity for 1D3D, 2D2D, and 1D2D cyclones.

Temperature	Calculated Cyclone Inlet Velocity (fpm)		
	1D3D	2D2D	1D2D
70°F	3,200	3,000	2,400
1,000°F	8,820	8,270	6,620

Calculations on cyclone performance reflect the effects of the extreme high temperatures of gasification. As velocity increases and the density of the gases decreases due to the increase in temperature, the cut point diameter is calculated to decrease. Table 2 shows the calculated cut point diameter at STP for a 1D3D or 2D2D cyclone is around 1.2 microns and around 2.4 microns for the 1D2D. As temperature increases, the cut point diameter is reduced and the cyclone collection efficiency improves. With the actual velocity around 8,800 fpm, this calculated cut point may not correctly represent the cyclone's performance, due to possible re-entrainment.

Table 2. Calculated Texas A&M Cyclone Design cut point (d_{pc}) for 1D3D, 2D2D, and 1D2D cyclones.

Temperature	Calculated Cut Point Diameter (µm)		
	1D3D	2D2D	1D2D
70°F	1.20	1.25	2.39
1,000°F	1.03	1.07	2.05

The results from the pressure drop calculations using the TCD process show a cause for concern in cyclone performance. Pressure drop increases with velocity and temperature. For temperatures of 1,000°F, the pressure drop is calculated to increase 275% from standard conditions (Table 3).

Table 3: Calculated Texas A&M Cyclone Design pressure drop (ΔP) for 1D3D, 2D2D, and 1D2D cyclones.

Temperature	Calculated Pressure Drop (in. w.g.)		
	1D3D	2D2D	1D2D
70°F	4.6	3.7	1.4
1,000°F	12.6	10.2	3.9

For a 1D3D and 2D2D cyclone the pressure drop will be 12 and 10 inches of water gage (in.w.g.) respectively. The 1D2D is calculated to have a pressure drop of 3.9 in.w.g.; although increased by a factor of 2.75 at 1,000°F, this remains in an acceptable range for operation.

Summary

The TCD process needs review for designing cyclones for the removal of bio-char from syngas produced by gasification. The significant decrease in density, caused by increased temperature, was calculated to affect cyclone performance. The TCD calculated cut point for bio-char will decrease at high temperatures, while the adverse increase in pressure drop across the cyclone would require greater fan power. Re-entrainment of collected PM in the exhaust gases may occur at high velocities from the syngas stream leaving the gasifier. Since the TCD process has not been tested at high temperatures, the need for verifying these calculated results is necessary before design work can continue.

Future Research

Simulating the high temperature syngas stream coming from the gasifier will be an effective model to test the TCD process and cyclone performance. Using the Texas A&M cyclone test stand (Figure 2), designed and constructed by Shane Saucier, it is possible to increase the air flow through a cyclone to match the inlet velocity from gasification. This system will allow for accurate measurement of collection efficiency and pressure drop. The test system is also capable of measuring number of turns in the outer vortex of the cyclone and the length of the gas stream to observe if particle re-entrainment is occurring.

Figure 2: Texas A&M cyclone testing system.

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