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Energy Consumption of Corn Stover Size Reduction

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Abstract. *Corn-based ethanol, the most common first generation biofuel in the US, plays an important role as a fossil fuels alternative. Second generation biofuels, which are mostly based on lignocellulosic biomass, have gained great attention in recent years. Size reduction of the lignocellulosic biomass is a key step to the efficiency of downstream processes (i.e., pretreatment, enzymatic hydrolysis, and fermentation), which will affect the yield of ethanol significantly. However, size reduction consumes considerable energy itself, it is an expensive process and needs to be optimized. Some studies have been done on corn stover size reduction, but none of them have examined the initial particle size of feedstock as a variable, and they failed to take the biomass harvest and storage conditions and downstream process requirements into consideration when setting the variables. The objective of this research was to study the effect of initial particle size of corn stover, moisture content, and screen size on energy consumption of corn stover size reduction. Consequently, these results should be generally applicable over a range of conditions that are affected by corn stover harvest and storage conditions and downstream processing.*

Keywords. *corn, biofuels.*

Introduction

Fossil fuels have been the main source of fuels for human since the beginning of last century; they are still counted for about 80% of total fuel consumption worldwide (Coldemberg 2007). However, according to a recent study, fossil fuel reserves will only last 35, 37, and 107 years for oil, gas, and coal, respectively (Shahriar Shafiee 2009). Besides, burning of fossil fuels is a large source of carbon dioxide and other green house gases (GHG) emissions (Hall and Scrase 1998). It is necessary and urgent to develop renewable fuels or energy as alternatives of fossil fuels that are less pollutant in terms of particulate, sulfur, lead emission and GHG emission (Coldemberg 2007). Nowadays, applicable renewable energy sources are hydro, biomass, wind, solar, geothermal, and marine tidal energy, of which modern biomass takes up 1.9% of total energy consumption in the world, while the total of other new renewable energy takes up only 1.5% (Coldemberg 2007). Modern biomass energy plays a more significant role compared to other available renewable energy sources because it can be converted to solid, liquid, or gaseous fuels that can be transported and utilized more easily than other energy sources (Hall and Scrase 1998). Corn ethanol is one of the most developed modern biomass energy industry, but its development has met some limitations.

A lot of attention has been paid on lignocellulosic ethanol production recently (Spatari, et al. 2010). Compared to corn ethanol, lignocellulosic ethanol has many advantages: wide availability of feedstocks, less controversies on land use change, and less environmental risk; while the key issue is to bring down the cost and make it profitable (Gnansounou and Dauriat 2010). Pretreatment, hydrolysis of cellulose and hemicellulose into monosaccharide, sugar fermentation, and ethanol recovery are the main steps of lignocellulosic ethanol production (Alvira, et al. 2010). However, due to the physical and chemical recalcitrance of lignocellulosic material, i.e., high lignin content as an enzyme barrier, high hemicellulose content, and crystallinity of cellulose (Hendriks and Zeeman 2009), digestibility of the material in these two processes is low if nothing is done before them (Taherzadeh and Karimi 2008). That's what makes pretreatment an extra and essential step compared to corn ethanol. In pretreatment process, particle size is reduced, lignin structures are broken down, and crystallinity of cellulose decreases, so that the accessibility and the potency of enzymes increase, as does the digestibility (Alvira, et al. 2010). On the other hand, pretreatment is costly; it is said to be the second most expensive step during the whole process (Mosier, et al. 2005). Looking for effective methods to bring down the cost of lignocellulosic biomass pretreatment is a major topic in many researches.

Of all the pretreatment methods, size reduction is an essential one; it increases surface area, bulk density, and flowability; reduces crystallinity and mass, heat transfer limitation of the biomass (Mani, et al. 2004). On the other hand, other pretreatment methods require biomass size reduction as a “pre-pretreatment”, e.g., dilute acid pretreatment, steam explosion pretreatment. (Harun 2011) (Öhgren 2006) However, it is unavoidably an expensive process, costing 13% to 28% of the total expenses along with transportation and storage (Miao, et al. 2011). Feedstock particle size, moisture content, material properties, mass feed rate, end size (screen opening), and machine parameters are the variables most relevant to effective specific energy consumption (Mani, et al. 2004). Some work has been done concerning the energy consumption of grinding different biomass materials with different physical properties using different mills and screens. Bitra et al. used a commercial knife mill as the grinder, took switchgrass, wheat straw, and corn stover as materials, set screen openings, rotor speed, and mass feed rate as variables; relationship between total specific energy and those variables was modeled and an optimum condition was determined from the model (Bitra, et al., 2009). A similar study was conducted by the same group using a hammer mill to process switchgrass, wheat straw, and corn stover at a constant mass input rate and fixed screen size, setting hammer speed and orientation as variables (Bitra, et al., 2009). Another study used biomass moisture content as one of the variables (Mani, et al. 2004).

Unfortunately, none of the related studies set the initial particle size of feedstock as a variable; besides, they failed to take the biomass harvest and storage conditions, i.e., moisture content, and downstream process requirements, i.e., particle size into consideration when setting the variables. Thus, the objective of this research was to study the effect of initial size of biomass, moisture content, and screen opening size on corn stover size reduction energy consumption; moisture content levels were set according to corn stover harvest and storage scenario and screen opening size levels were set to match with the requirement for the following pretreatment process.

Materials and Methods

Biomass

In this study, freshly harvested, air-dried corn stover round bales were supplied from central Iowa and stored in ambient temperature.

Grinder

A knife mill modeled Thomas Model 4 Whiley® Mill 3375-E15 (120V, 800rpm, Thomas Scientific, Swedesboro, NJ) was used in this study.

Power Meter

Energy consumption data was obtained using Watts Up® PRO power meter (ThinkTank Energy Products Inc. Milton, Vermont). Power was recorded every second when the knife mill was in operation.

Grinding variables

Initial size of corn stover

Stalks, leaves, and husks were cut by band using metal scissors; they were sorted into three sizes of large (L, 4~7cm), medium (M, 7~10cm), and small (S, 8~18cm), together with different sizes of cobs within the bale.

Moisture content

The initial moisture content of corn stover was determined according to ASABE standard S358.2 DEC 98 for forages (ASAE, 1999). Three samples of 25 grams were dried in oven at 105±3°C for 24 hours. The average of the three samples was recorded in percent wet basis.

After the determination of initial moisture content, corn stover of L, M, and S sizes were put into separate plastic zip bags. The amount of water needed in order to get the objective moisture content was calculated based on the original moisture content and the weight of samples that were put into the bags. Then water was added on the biomass evenly; the bags were well sealed and stored in ambient temperature for 72h to get equilibrium moisture content (Mani, et al. 2004).

Moisture content of 5.17% (original moisture), 10%, and 20% (all in wet basis) were set for this study. Typically, corn stover is harvested at moisture content of 20% to 25% as dry product and packaged as dense round bales or loose stacks (Shinners, et al. 2007). According to Nielson, corn stover moisture content should be 20% or less for storage (Niel, 1995). Another research conducted by Iowa State University indicates that the corn stover of moisture content less than 25% has less storage loss for both tarped and under roof storage method (Shah and Darr, 2014). According to these facts, moisture content of 20% was chosen for this study; 10% was also chosen to fill the gap between 20% and 5.17%.

Screen

Screens of 2mm and 6mm opening sizes were used in this study. In the studies conducted by Öhgren, particle size of 2mm to 10mm was used for steam pretreatment of corn stover (Öhgren, et al. 2006, 2007). In another study, rice straw was ground to less than 10mm for extrusion/expansion pretreatment (Chen, et al. 2011). In addition, switchgrass and corn stover was reduced to 60mesh (0.25mm) to 20mesh (0.85mm) for hydrothermal pretreatment (Kumar, et al. 2011). Considering the facts above and the availability of interchangeable parts for the knife mill, 2mm and 6mm screens were the optimal choice for this study.

Data analysis

Original data was transferred from the power meter to a computer connected by a USB cord. Watts UP® USB Data Logger software was used to assist the process. Specific energy is obtained by the equation (1):

$$SE = \frac{\int_0^t (P - \mathrm{P}0)\, dt}{m} = \frac{\int_0^t \Delta P dt}{m}$$

where SE is the specific energy, t is the grinding time, P is the power when the material is being grinded, P_0 is the idle power of the grinder, m is the mass of corn stover (Miao, et al. 2011). SAS® GLM procedure was used for data analysis. The effects of each variable and their interactions were analyzed.

Results and Discussion

Table 1. Specific Energy Consumption (joule/g) for Each Treatment

Screen	2mm			6mm		
Moisture/Size	L	M	S	L	M	S
	186.4	199.1	167.7	91.6	104.5	117.6
5%	173.6	203.0	182.5	111.6	100.4	137.6
	190.8	170.8	196.6	123.6	123.3	129.5
Average of 5%	183.6	191.0	182.2	108.9	109.4	128.2
	288.0	336.1	433.3	248.0	261.4	258.0
10%	529.8	506.0	340.4	214.0	178.8	229.5
	339.8	412.4	443.5	199.1	186.2	211.1
Average of 10%	385.9	418.2	405.7	220.4	208.8	232.9
20	838.6	954.0	812.0	556.2	585.7	519.8

As shown in table 1, specific energy was calculated using equation (1) in joule (watt*second) per gram of biomass. It can be converted to kilowatt*hour per metric ton by a dividing factor of 3.6. ‘Size’ stands for initial size of corn stover. From table 2 we can see the p-values for ‘Size’ and the interaction between ‘Size’ and other variables are larger than 0.1, which shows no significant effect of those factors. P-values for moisture, screen, and the interaction between moisture and screen are less than 0.0001, which shows strong evidence for the significant effects of moisture, screen, and their interaction on specific energy consumption of corn stover grinding.

Figure 1 shows the interaction between moisture and screen opening size. The blue line and red line are not parallel with each other, which indicates the existence of interaction between the two factors. Figure 2 shows the mean value for each level of moisture and screen opening. Figure 3, 4, 5 show the box-plots of effects of each individual factor.

Table 2. ANOVA Table for Each Variable and Their Interactions

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Moisture	2	1418212.206	709106.103	273.95	<.0001
Screen	1	289272.064	289272.064	111.75	<.0001
Size	2	6482.485	3241.242	1.25	0.3039
moisture*screen	2	73881.001	36940.500	14.27	<.0001
moisture*size	4	10469.771	2617.443	1.01	0.4213
screen*size	2	3827.181	1913.590	0.74	0.4880
moisture*screen*size	4	1394.128	348.532	0.13	0.9680

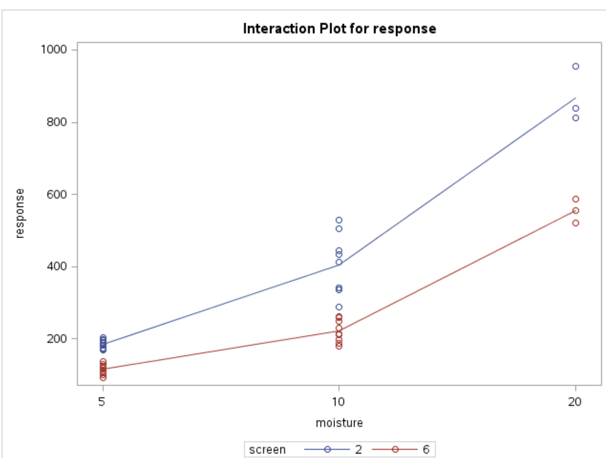

Fig. 1. Interaction Between Screen & Moisture

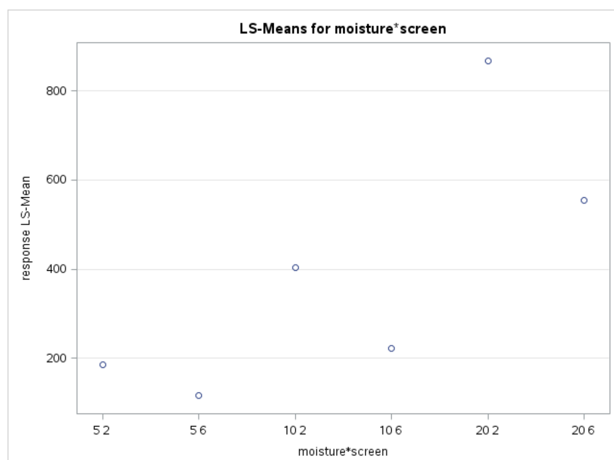

Fig. 2. Least Square Means for Screen & Moisture

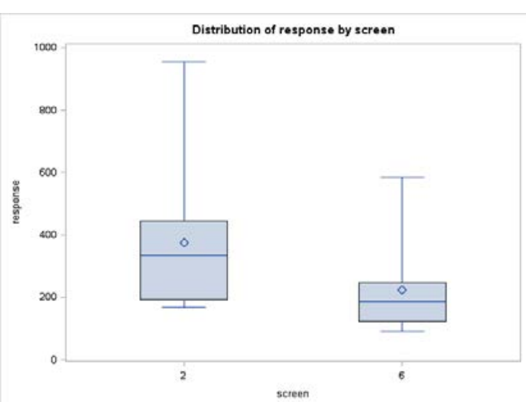

Fig. 3. Effects of Screen

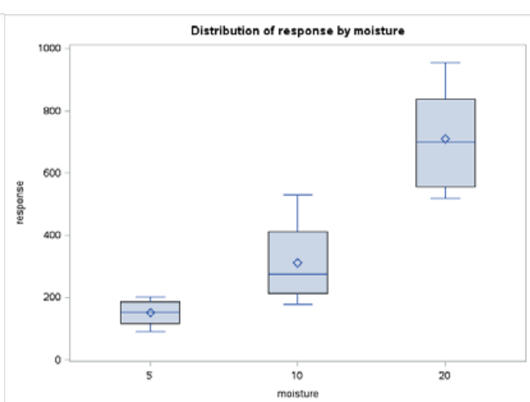

Fig. 4. Effects of Moisture

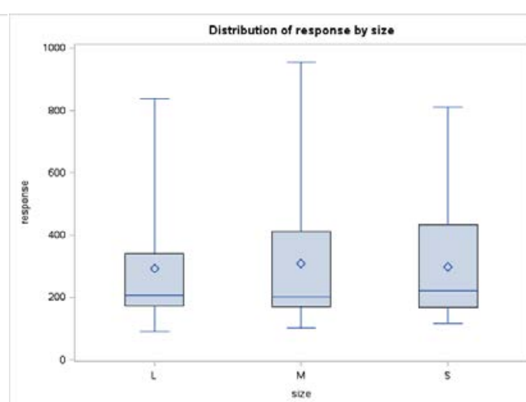

Fig. 5. Effects of Initial Size

Conclusion

In this study, the effects of three factors on corn stover size reduction energy consumption were discussed. The initial size of corn stover was the novel variable that has not been discussed in other works. It turned out that the initial size of biomass had no significant effect on specific energy consumption. This suggested skipping or reducing unnecessary coarse grinding process before fine grinding, as long as the initial size of biomass can fit into the fine grinder and will not cause clogging or other malfunction of the grinder. Levels of other two factors were determined according to the harvest and storage conditions of the biomass and the downstream processing requirement on the biomass. Moisture content and screen opening size (final size after grinding) both had significant effects on specific energy, so did their interaction. Higher moisture content and smaller screen opening will end up with higher energy consumption. Not taking economic factors into account, biomass should be as dry as possible prior to size reduction. Size of biomass for pretreatment should be as large as possible at the least expense of decreasing the effectiveness of pretreatment.

The amount of corncobs in the corn stover was found to have a big influence on the final result during our experiments, so further study can be designed to test the effect of the cob ratios in corn stover on specific energy consumption of size reduction.

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