The Pennsylvania State University

The Graduate School

College of Engineering

ENERGY CONSUMPTION STUDY ON BULK DENSIFICATION OF HERBACEOUS BIOMASS CROPS

A Thesis in

Agricultural and Biological Engineering

by

Tianyi Wang

Submitted in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science

December 2014

This thesis of Tianyi Wang was reviewed and approved* by the following:

Jude Liu

Associate Professor of Agricultural and Biological Engineering

Thesis Advisor

Virendra Puri

Distinguished Professor of Agricultural and Biological Engineering

Marvin Hall

Professor of Forage Management

Paul Heinemann

Professor & Department Head of Agricultural and Biological Engineering

*Signatures are on file in the Graduate School

Abstract

Switchgrass and Miscanthus are well known as energy crops, and corn stover is also used as energy biomass feedstock. These bulky biomass crops need to be densified in order to reduce costs associated with storage, handling, and transportation.

However, over densification may cause a waste of energy and money. A reasonable volume reduction is needed for an efficient production of bulk densification. In this study, the values of volume reductions were suggested considering various biomass crops and harvesting times.

The energy consumption of compressing baled biomass with 170 kg/m^3 initial density has been studied. However, the energy consumption performance with an initial density lower than 170 kg/m^3 biomass material is still unknown. In order to scale up the curve, loose biomass material needs to be tested.

Five cuboid compression chambers with different dimensions were used to test the energy consumption of compressing bulk biomass and to determine the impact of compression chamber size on the energy consumption of compressing bulk biomass materials. The result could also scale up the curve of energy consumption vs. chamber size. Biomass crop samples were collected from fields and cut into different lengths before tests. Crop samples with a certain cut length were filled into a chamber with the same initial bulk density, which were around 40 kg/m^3 to simulate the bulk density of windrowed crops in the field. The relationships between specific energy consumption and compression chamber size were determined. Results indicated that larger compression chamber had significant lower specific energy consumption during the bulk compression process.

The particle length and particle orientation were also considered while testing on the energy consumption during compression process. Particle lengths indicate the cut length of biomass crop samples. Crop samples were cut into different lengths referred to as particle sizes. For each compression chamber, crop samples were divided into three groups according to the cut length and orientation methods. Group 1 crop samples were cut into the same length with the width of the compression chamber, and all crops were laid flat and arranged parallel to a sidewall of the chamber. Crops in the group 2 had the same length, but they were randomly laid flat into the chamber. Crops used for Group 3 were cut into 50-mm (2-in) long pieces, and they were also randomly laid in the chamber. Groups 1 and 2 were used to examine the effect of arrangement methods on the compression process. Groups 2 and 3 were designed to study the effect of particle size on the compression process. Results demonstrated that the parallel arrangement method needed less compression energy; and the biomass with shorter particle sizes had higher specific energy consumption than those longer ones.

The harvest season of energy crops was also considered as a factor which could impact on the compression energy consumption. Test results indicated that there was no energy consumption difference between 2013 fall and 2014 spring harvested Switchgrass. In addition, corn stover samples collected in 2013 October and December were also tested, and different energy consumption values were detected due to these two months in snow season. .

Table of Contents

List of Figures vii

List of Tables ix

Acknowledgments x

Chapter 1 - Introduction and Justification 1

Chapter 2 - Literature Review and Synthesis 3

- 2.1 Introduction 3
- 2.2 Biomass as an Alternative Energy Source 3
  - 2.2.1 Prospect of biomass 3
  - 2.2.2 The significant contribution of using biomass as energy sources to reducing the greenhouse effect 4
  - 2.2.3 Herbaceous biomass as a fuel source 4
- 2.3 Biomass densification 6
  - 2.3.1 Extruding densification 6
  - 2.3.2 Pelleting densification 6
  - 2.3.3 Cubing densification 7
- 2.4 Effect of moisture content on densification 7
- 2.5 Effect of grind size on densification 8
- 2.6 Specific energy for biomass densification 8
- 2.7 State of the art 9

Chapter 3 - Goals, Objectives, and Hypotheses 10

- 3.1 Research Goal 10
- 3.2 Research Objectives 10
- 3.3 Research Hypotheses 10

Chapter 4 - Materials and Methodology 12

- 4.1 Procedure 12

4.2 Crop sampling and preparation 14
    4.2.1 Field crop sampling 14
    4.2.2 Compression chamber 15
    4.2.3 Sample preparation 16
    4.2.4 Arrangement of crop samples in compression chambers 16
4.3 Experimental facilities and measurements 17
    4.3.1 Universal testing machine 17
    4.3.2 Measurements 19
4.4 Experimental design 20
4.5 Data collection and analysis 21
Chapter 5 - Study of Switchgrass Compression 23
5.1 The energy consumption using different sized chambers 24
5.2 Comparison between the arrangement and particle size 27
5.3 A case study of seasonal difference 30
Chapter 6 - Study of Corn Stover Compression 32
6.1 The energy consumption study using different sized chambers 32
6.2 Comparison between the arrangement and particle size 34
6.3 A comparison of compression energy consumption between October and December harvested corn 35
Chapter 7 - Study of Miscanthus Compression 37
7.1 The energy study of different size chamber 37
7.2 Comparison of the arrangement and particle size 44
Chapter 8 - Comparison between crops and suggested compression volume reduction 47
8.1 Comparison of compression specific energy consumption between crops 47
8.2 Suggested compression volume reduction 47
Chapter 9 – Conclusions and Recommendations 52
Reference: 54

List of Figures

Figure 4. 1. Methodology flow chart for energy crops densification. 13

Figure 4. 2. Switchgrass bundling in the field. 14

Figure 4. 3. Post-combined Corn stover lying in the field. 15

Figure 4. 4. The chambers of different size (left to right: V, IV, III, II, I). 16

Figure 4. 5. The materials were arranged horizontally in the same direction................. 17

Figure 4. 6. The materials were arranged randomly. 17

Figure 4. 7. The T-Rex machine compressing biomass. 18

Figure 5. 1. Compression force vs. displacement graph (5.1cm miscanthus, Chamber V). 25

Figure 5. 2. Compression force vs. displacement graph (14cm switchgrass, Camber I). 25

Figure 5. 3. Specific energy consumption (MJ/Mg) graph of switchgrass compressed in five different size chambers.. 27

Figure 5. 4. Comparison of switchgrass between the arrangement and particle size. 30

Figure 5. 5. Compression energy consumption comparison between spring 2014 and fall 2013 harvested switchgrass. 31

Figure 6. 1. Specific energy consumption (MJ/Mg) graph of Oct. harvested corn stover compressed in five different size chambers. 33

Figure 6. 2. Specific energy consumption (MJ/Mg) graph of Dec. harvested corn stover compressed in five different size chambers. 34

Figure 6. 3. The comparison between particle sizes and arrangement methods (Mean of five chamber size, Miscanthus). 35

Figure 6. 4. The comparison between two harvested time corn stover (Mean of Chamber I, III, IV). 36

Figure 7. 1. Specific energy consumption (MJ/Mg) graph of parallel long miscanthus

particle compressed in five different size chambers (Group1). 39

Figure 7. 2. Specific energy consumption (MJ/Mg) graph of random long miscanthus particle compressed in five different size chambers (Group2). 41

Figure 7. 3. Specific energy consumption (MJ/Mg) graph of random 2-inch miscanthus particle compressed in five different size chambers (Group3). 43

Figure 7. 4. The effect from arrangement and particle size on miscanthus compression (1, 2, 3 in legend stand for Group 1, 2, 3 respectively). 45

Figure 8. 1. Energy consumption vs. displacement graph of 14cm switchgrass in a small camber (15.2cm x14cm x20.3cm) 48

Figure 8. 2. Specific energy consumption interval plot of Switchgrass at 60% Volume reduction. 50

Figure 8. 3. Specific energy consumption interval plot of Corn stover at 60% Volume reduction. 51

List of Tables

Table 4. 1. Details of experimental design for Switchgrass... 20

Table 4. 2. Details of experimental design for Corn stover. 21

Table 4. 3. Details of experimental design for Miscanthus. 21

Table 5. 1. Specific energy consumption of switchgrass at 60%, 70%, 80%, and 88% Volume reduction... 23

Table 5. 2. Specific energy consumption of switchgrass at 88% volume reduction........ 26

Table 5. 3. Specific energy consumption of 2013 harvested switchgrass at 88% volume reduction.. 30

Table 6. 1. Specific energy (MJ/Mg) consumption of corn stover at 60%, 70%, 80%, and 88% Volume reduction. 32

Table 7. 1. Specific energy consumption (MJ/Mg) of miscanthus at 50%, 60%, 70%, and 80% Volume reduction. 37

Table 7. 2. Specific energy consumption (MJ/Mg) of miscanthus at 80% volume reduction.. 38

Table 8. 1. Specific energy consumption (MJ/Mg) comparison between switchgrass, corn stover, and miscanthus.. 47

Table 8. 2. Suggested Volume reduction & Specific energy consumption...................... 49

Table 8. 3. Specific energy consumption of Switchgrass at 60% Volume reduction....... 50

Table 8. 4. Specific energy consumption of Corn stover at 60% Volume reduction. 51

Acknowledgments

I would like to thank my advisor, Dr. Jude Liu for providing me an opportunity to study in the biomass area at the Pennsylvania State University and guiding me patiently in the past two years. I learned not only the knowledge in this research area but also the methodology of research. I also want to thank my committee members, Dr. Virendra Puri and Dr. Marvin Hall. They did give me lots of good suggestions to improve my research.

I would like to thank many people who provided help during my research. Dr. Roderick Thomas helped me program the LabVIEW software; Mr. Randall Bock gave me good advises while I was building the compression chambers in the workshop. Zhao Zhang and Xinmiao Wang also assisted me a lot with the crop collection.

The last but not the least, I am grateful to my parents and my friends. They always provided me the strongest support.

Chapter 1 - Introduction and Justification

Facing the global energy risk, sustainable energy systems need to be developed. Sustainable energy includes renewable energy sources, such as hydroelectricity, solar energy, wind energy, wave power, geothermal energy, and bioenergy.

According to a report from Environmental Protection Agency (EPA, 2012), the renewable fuel standard was 7.76% in 2008, which means about nine billion gallons of renewable fuels to be blended into transportation gasoline. This value was increased to 10.21% in 2009, which indicates about 11.1 billion gallons of renewable fuels will be blended into transportation gasoline. There will be 500 million gallons of biomass-based diesel fuel to be blended into diesel fuel in 2009. In fact, one billion gallons biomass-based diesel and two billion gallons advanced biofuels, which approximately occupy 0.91% and 1.21% of total primary energy consumption respectively, were required in USA in 2012, while the fossil fuel occupies as high as 82% of total primary energy consumption. Obviously, biofuel production and related technology are still needs to be developed in the future.

Biomass residues in agriculture have potential to be converted into biofuel and counteract parts of greenhouse gas emission (Campbell et al., 2002; Sokhansanj et al., 2006). Traditionally, the agricultural residues were regard useless and need to be disposed as waste. However, the residues can be treated as economically, abundant and readily available source of renewable energy (Liu et al., 2005).

The loose biomass is hard to be handled, transported and stored because of the variable and different sizes and forms (Sokhansanj et al., 2005). As a result, the biomass compaction which can uniform the biomass into particular shape and size is critical and desirable operation (Adapa, 2009). According to previous studies, biomass which is compacted into uniform shape and size can be handled by using standard storage and handling instrument easily (Mani et al., 2003).

For the purpose of withstanding various forces and impact during handling and transportation processes, density and durability as dependent quality index with independent variables such as, moisture content, are desired to be predicted (Adapa et al., 2007). Compactions with control of biomass physical and chemical characteristics have relatively high quality (Adapa, 2009). In order to compress the biomass efficiently, the characteristics of biomass should be understood more deeply and completely (Sokhansanj et al., 2005).

With the purpose of processing biomass energy crops which could extremely reduce the pressure of energy shortage (Caparella, 2012), reducing the cost and increasing the net output of energy are desired. A physical analysis of biomass bulk densification will be investigated.

Chapter 2 - Literature Review and Synthesis

2.1 Introduction

Development and research of harvesting, transportation and processing biomass economically and efficiently have been going on for several years (Kemmerer, 2011). To accomplish these tasks, two fundamental issues to be solved are: (1) the cost of the field operations needs to be reduced as much as possible, and (2) more efficient harvesting systems and densification methods are needed.

In order to reduce the cost of industrial operations, biomass should be handled in an efficient way (Adapa, 2009). Because of the low density and diverse sizes and shapes of biomass feedstocks, it is not easy to handle, transport and store biomass without densification (Sokhansanj et al., 2004). Densification is an effective way to solve handling difficulties as well as reduce the mass loss of biomass materials (Adapa, 2009). For densification, improper compression may cause dusty process, poor handling and high cost. This is mainly resulted from lack of adequate understanding physical and chemical properties of biomass during compression (Sokhansanj et al., 2005).

2.2 Biomass as an Alternative Energy Source

Biomass, biological material from living plants, is a renewable energy source (BEC, 2012). The biomass is usually converted into other energy products as an energy resource. There are lots of agricultural biomass crops such as sorghum, corn, and energy crops such as miscanthus, hemp, poplar, willow, bluestem, sugarcane, switchgrass, and bamboo.

2.2.1 Prospect of biomass

Biomass performs impressively as a renewable energy source which is intensively used to substitute fossil fuels such as coal, petroleum, and natural gas (Mani, 2003). A review from Bechen (2011) showed that the continued development of the biomass industry in the European

Union and other areas of the world are expected. By far, the United State leads the world in biomass production capacity in both quantities and utilization; however, that is starting to change. The North American woody pelletizing industry has become a major supplier to the European Union. The volume of EU-bound wood pellet shipments in 2010 was doubled that of 2008, with the Netherlands, the United Kingdom and Belgium leading the demand. From 2008 to 2009 the E.U.'s gross electricity production from biomass increased more than 10%, with Germany, Sweden and the U.K. leading the way. The U.K., in particular, is focusing its efforts on developing its biomass capacity. October saw the U.K. propose subsidies to business customers (to be followed by households after the program was established) who use renewable energy technology for heating. While the program's rich subsidy was scaled back (from 2.7 pence per kilowatt hour (kWh) to 1 penny per kWh), the efforts show clearly that the political will is in place to continue to support the biomass industry (Bechen, 2011). The U.K.'s proposals included as a key goal the development of "cheaper" renewable generation, focusing specifically on the conversion of coal plants to biomass and co-firing plants.

2.2.2 The significant contribution of using biomass as energy sources to reducing the greenhouse effect

Large amounts of carbon dioxide are produced when using traditional fossil energy fuel such as coal, gasoline or natural gas. The carbon dioxide emission is possibly the second largest contributor to global warming (Zhang, 2007). However, using biomass as energy sources could avoid these happening. The emission and absorption of carbon dioxide is the same during biomass energy using system. In other words, using bio mass as energy sources won't increase additional carbon dioxide.

2.2.3 Herbaceous biomass as a fuel source

Previous studies (Liu, 2012) of herbaceous biomass show the costs of harvesting feedstock are a key cost component in the logistics supply chain for biomass fuel. The window of harvest based on weather and growing conditions limits harvesting of herbaceous biomass to set periods during the summer and early fall, thereby making this a seasonal process.

2.2.3.1 Switchgrass

Switchgrass (*Panicum virgatum*) is perennial warm season grass energy crop native to North America. This crop has been researched as a renewable bioenergy crop since the mid-1980s, because it is a native perennial warm season grass with the ability to produce moderate to high yields on marginal farmlands. The harvest is once a year and the grass are commonly cut with a mower conditioner (TSEC, 2001). People use switchgrass to produce biofuel, electricity or heat (McLaughlin, 2005). As a result, the energy output of switchgrass must be much more than energy cost of planting, harvesting, and processing, so that the whole processes of switchgrass production for fuel make sense. This study will focus on why switchgrass can be regarded as an energy crop, what should be considered in switchgrass harvesting and processing processes and what should be measured will be descripted.

Switchgrass has an 18,300 MJ/Mg net calorific value of dry matter, which equals 0.6-0.8 Mg of coal (this value may vary with different coal grade). A model of switchgrass is made for considering the energy inputs (MJ) and the biomass energy output (MJ) during a 20-year cropping period (TSEC, 2001). The ratio of energy output from the harvested biomass to energy input to reach the biomass was 28.9 during the 20-year period (TSEC, 2001); and, the heat efficiency was high as 80% (FPL, 2004). As a conclusion, switchgrass is an ideal energy crop.

2.2.3.2 Miscanthus

Miscanthus is a perennial grass native to southern Asia and subtropical and tropical regions of Africa. The solid pith stem grow rapidly. The harvest of miscanthus is once a year between January and March. This grass is usually mowed with a mower conditioner.

Miscanthus has a net calorific value of 17,000 MJ per Mg dry weight, which equals to 0.6-0.8 Mg of coal (this value may vary with different coal grade). The ratio of energy output from the harvested biomass to energy input to reach the biomass was 35.9 during the 20-year period (TSEC, 2001). Compared with switchgrass, miscanthus demands more energy during establish stage but the high yields gives this crop a higher long-term energy return.

2.3 Biomass densification

In order to use biomass as an energy source, the challenge is that the original form of biomass material cost too much for handling and transporting. One way to solve this problem is to densify biomass materials, such as briquetting, pelletizing, or cubing (Kaliyan & Morey, 2006a). Densification increases the bulk density of biomass from a density of 40-200 kg/m^3 to a density of 600-800 kg/m^3 (Holley, 1983; Mani et al., 2003; Obernberger & Thek, 2004; McMullenet al., 2005; Adapa et al., 2007). As a result, biomass densification is able to reduce the costs of handling, transportation, and storage. Due to uniform sizes and shapes of densified biomass, the material can be easily handled with standard machines or equipment which makes the process more efficient (Kaliyan & Morey, 2006a).

2.3.1 Extruding densification

In extruding densification, conventionally the raw material is compressed by piston or crew into a cylindrical die. The diameter of extrusion products often range from 20 to 100 mm. This technology is commonly applied in Asian countries such as, Japan and India, for biomass densification (Bhattacharya, 1985; Grover, 1996; Varadharaju, 1998).

2.3.2 Pelleting densification

During pelleting densification, the feed material is pressed though cylindrical die with both ends opened. Small rotating rolls press the biomass material into dies from one end to the other. The friction which is produced by material and inter surface of sidewall balance the pressure to form the pellets finally. The pellets would be cut into desired length by the knives which are placed outside of the output end of die. The diameter of pelleting products often range from 4.6 to 19.0mm, and length range from 12.7 to 25.4mm (Kaliyan & Morey, 2006a). The unit density may range from 960 to 1,120 kg/m^3, while the bulk density may as high as 700 kg/m^3 (Sokhansanj, 2004). This technology is commonly applied in U.S. and Europe for animal feed.

2.3.3 Cubing densification

Cubes are larger sized pellets, commonly form of square cross section of chopped biomass material and the cuber usually has one row of holes in the die ring (Sokhansanj, 1991). Cubes sizes range from 12.7 to 38.1 mm in cross section and the length of cube is usually equal to or longer than dimensions of cross section, commonly from 25.4 to 101.6 mm. The bulk density of cube is ranging from 450 to 550 kg/m^3 which are less than pellet (Sokhansanj, 2004; Kaliyan & Morey, 2006a).

2.4 Effect of moisture content on densification

The moisture content acts as a facilitator of binding agents as well as a lubricant (Kaliyan & Morey, 2006a). Moisture content of 8-9% (w.b.) was recommended as an optimum value for producing high quality alfalfa pellets; and moisture content of 11-12% (w.b.) was generally applied for wheat-based and corn-based pellets (Stevens, 1987). Moisture content of 6-12% (w.b.) especially 8% was good for producing good quality wood logs (Li, 2000). Obernberger (2004) concluded that it is possible to produce high quality pellet only if the moisture content of feedstock is 8-12% (w.b.). The biomass material with moisture content which is out of this range would lead relatively low quality pellets.

Kaliyan and Morey (2006b) conclude that there is no significant difference in corn stover briquette densities with 10 and 15% moisture contents under 100 MPa. However, under 150 MPa the densities decreased with increasing moisture from 10 to 15%. For switchgrass, 30-40% densities decreased with moisture content increasing from 10 to 15%. Mani et al. (2002) also observed similar result that increased moisture content leads decreased biomass density of corn stover, switchgrass, wheat straw, and barley straw. Mani et al. (2006) also observed highest briquette density of 950 kg/m^3 for corn stover with 5-10% moisture content. And another conclusion that high moisture content of 15% under 15MPa led a negative effect on briquette density was also drawn in the same study. Grover and Mishar (1996) also recommended low moisture content (8-10%) to produce briquettes. Kaliyan and Morey (2007) observed the bulk density of compacts for corn stover and switchgrass decreased with increased moisture content which range from 7 to 15% and 9 to 20%, respectively. And low moisture (10%) was recommended for good quality compacts.

2.5 Effect of grind size on densification

Kaliyan and Morey (2006a) observed that good quality of compact was resulted from the proper grind size. Large particle size of biomass compact may cause cracks and fractures (MacBain, 1966). Kaliyan and Morey (2006b) reported that particle size of corn stover decreased from 0.80 to 0.66 mm led briquette densities increased by 5 to 10%. Mani et al. (2002, 2004) observed similar result that pellet size increased from 0.8 to 3.2 mm with density decreasing by 5 to 16%. However, there is no significant impact on briquette density for switchgrass with particle size of 0.64 to 0.56 mm. Mani et al. (2002) has the similar conclusion for switchgrass pelleting with sizes of 0.25 to 0.46 mm.

2.6 Specific energy for biomass densification

Mani et al. (2004) indicated that the energy consumption of biomass densification depends on applied compressing pressure and moisture content of biomass material as well as physical properties of biomass material and method of densification. Mani et al. (2006) compressed corn stover into briquettes, which had a density of 650-950 kg/m^3, and 12-30MJ/Mg was required during the compression. The energy of resistant friction was about a half of the total energy. Mewes (1959) reported the similar conclusion that around 60% of total energy was consumed to overcome friction. For alfalfa, Bellinger and McColly (1961) indicated that only 10-15% of total energy was consumed on compressing, which means the most of energy consumed was used to overcome friction.

O’Dogherty and Wheeler (1984) indicated that barley straw compression required 5-25 MJ/Mg as specific energy consumption. Faborode and O’Callaghan (1987) reported that chopped and un-chopped barley straw with 8.3% moisture content required 28-31 MJ/Mg and 18-27 MJ/Mg, respectively. Kaliyan and Morey (2006b) reported that the specific energy consumption for switchgrass briquetting decreased from 189 to 187 MJ/Mg with particle size decreasing from 0.64 to 0.56 mm at pressure of 150MPa. Wang (2012) reported that the specific energy consumption of Leymus chinenis briquetting decreased from 9.1 to 7.9 MJ/Mg with moisture content increasing from 7 to 12% (w.b.) at a pressure of 10 MPa.

2.7 State of the art

Utilizing biomass to convert into energy has been studied for a number of years. Large numbers of studies were focused on the effect of physical and chemical characteristics on biomass densification. Most of these studies were concentrated on the effect of moisture content and pressure on the densification density and energy consumption. Some research activities were about the effect of particle size of chopped materials on density and energy consumption. However, study on biomass densification rarely explored physical characteristics of large sizes of biomass densification such as bales or raw material bulk densification. Large size densification commonly was referred to as initial densification which is directly relative to biomass handling, transportation, and storage especially in field.

In addition, Corn stover and wheat straw also draw researchers' attention because people want to make full use of these crop residues after grain harvesting. Relatively speaking, fewer studies are directly related to energy crops especially herbaceous energy crops which have much more reproducibility (Liu, et. al., 2012). Depending on the differences of soil, moisture and climate conditions in a specific area, different energy crops are chosen. Miscanthus and switchgrass are known as an adaptable and high yield energy crops.

The energy consumption of densifying biomass materials, which is a very important issue of energy crop production, has not been studied sufficiently so far. A thorough study on the mechanical properties of energy crop densification should be conducted to seek for ways to reduce the investment cost and energy consumption during densification production.

Chapter 3 - Goals, Objectives, and Hypotheses

There have been studies using densification to handle biomass. The factors, which could influence the process of densification, were also considered fully, such as moisture content and the form of biomass. However, the size of the compression chamber used to densify bulk biomass materials has not been considered as an important factor which could affect the energy consumption during bulk densification.

3.1 Research Goal

The goal of this research was to investigate the mechanical properties of energy crops during bulk densification. Relationships between the size of the compression chamber and the specific energy consumption are to be determined in this study. Raw biomass materials were chosen as experimental materials. The size of the compression chamber was a main factor to be analyzed in this study. Other factors included particle size or cut length of the biomass crops, and the arrangement method of these crops in the compression chamber. The variety of biomass crops was also considered in this study.

3.2 Research Objectives

The objectives of this research were to:

1. Develop the relationships between the specific energy of compressing bulk biomass crops and the bottom areas of compression chambers.
2. Quantify the influence of particle size (cut length) and arrangement methods of biomass on the energy consumption during densification process.
3. Characterize the differences between densifying different biomass crops.

3.3 Research Hypotheses

Hypotheses to be evaluated in this research are:

1. H_0: Size of chamber does not significantly (α =0.05) influence on specific energy

consumption.

H_a: Size of chamber significantly influences on specific energy consumption.

2. H_0: The particle size of biomass material does not significantly (α =0.05) influence on specific energy consumption.

H_a: The particle size of biomass material significantly influences on specific energy consumption.

3. H_0: The variety of biomass material does not significantly (α =0.05) influence on specific energy consumption.

H_a: The variety of biomass material significantly influences on specific energy consumption.

Chapter 4 - Materials and Methodology

This section will discuss the details of methods which intend to fullfill each objective and goal.

4.1 Procedure

Figure 4.1 systematically describes the methods for completing the proposed work. Phase 1 determines the framwork of experiment and what data to be collected.

Phase 2 indicates two experimental steps: preloading and loading. The preloading was the process of filling a certain amount of samples into the compression chamber to achieve the same initial bulk density for all tests. Vertical load and displacement or energy consumption were measured in both loading steps

Phase 3 includes the calculation and evaluation of specific energy consumption. Energy consumption is calculated from the area surrounded by a load-displacement curve measured from a compression test (O’Dogherty, 1984, 1989).

Phase 4 involves the development of relationships between chamber size and specific energy consumption for different biomass crops.

Phase 5 considers the impact of crop forms (particle length) on compression energy. Three crops are chopped into 2 inch long, and the length exactly the same as the chamber width 14cm (5.5in), 16.5cm (6.5in), 19.1cm (7.5in), 22.9cm (9in) and 25.4cm (10in).

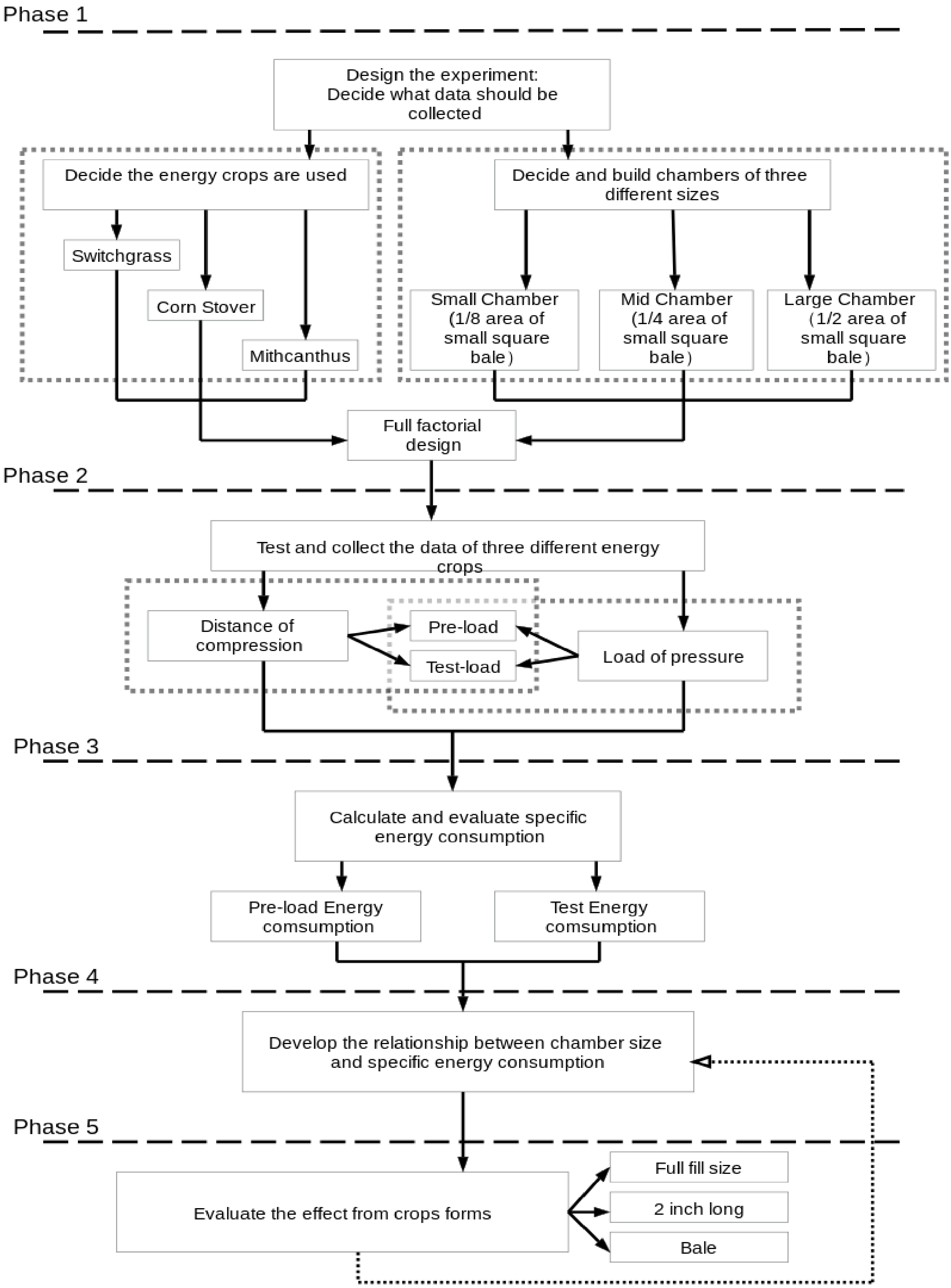


Figure 4. 1. Methodology flow chart for energy crops densification.

4.2 Crop sampling and preparation

4.2.1 Field crop sampling

The materials were all collected in central Pennsylvania area. The fall switchgrass samples were manually cut using garden shears during November to December 2013. The switchgrass was cut at 10.2-15.2 cm from the ground surface, and then bundled with tape for transportation (Figure 4.2). The switchgrass samples collected from the field were brought back the lab and kept in a cold storage room which was located in Agricultural and Biological Engineering building at Penn State. Switchgrass was left standing over the winter in the field, and then samples were collected in the spring (March, 2014) with the same method.

Figure 4. 2. Switchgrass bundling in the field.

Corn was combined in October 2013 and the stover was left in field (Figure 4.3). Corn stover samples were then collected between November and December 2013. The corn stover samples were collected by hand and also stored in the same cold room as the switchgrass. The spring corn stover samples were collected in March 2014 from the same field, where corn was combined in October 2013.

Figure 4. 3. Post-combined Corn stover lying in the field.

Miscanthus samples were only collected in the spring. Miscanthus crops were standing in the field over the winter, and were cut using garden shears in March 2014. Crop samples were also stored in the same cold room as switchgrass.

4.2.2 Compression chamber

To evaluate the effect of chamber size on thespecific energy consumption, five compression chambers with different sizes were made as shown in figure 4.4. The cross sectional area of these chambers were 1/2, 3/8, 1/4, 3/16 and 1/8 of the compression chamber of a small square baler (1625.8cm^2). The heights of chambers were also modified depend on chambers' cross sectional area to make sure the chambers are all in the similar shape. Thus, five cross sections of these chambers were, 30.5cm x 26.7cm x 40.6cm, 24.1cm x 25.4cm x 31.8cm, 20.3cm x 20.3cm x27.9cm, 17.8cm x 17.8cm x 24.1cm ,and 15.2cm x 14cm x20.3 cm respectively, and named as chamber V, IV, III, II, I (Chamber V is the largest, and Chamber I is the smallest) in following part of thesis for convinient description (Figure 4.4).

The chambers were built with carbon steel plate to ensure the strength. Each chamber had its matched compression head, and the chamber body was welded.

Figure 4. 4. The chambers of different size (left to right: V, IV, III, II, I).

4.2.3 Sample preparation

For each compression chamber, the raw crop samples were cut into two lengths. One length was 5.1cm (2 inch), and the other was the same width as the chamber. Three chamber sizes, 14cm (5.5in), 19.1cm (7.5in), and 25.4cm (10in), were used for compressing all crops. For Switchgrass and Miscanthus, two more chamber sizes and crop lengths, 16.5cm (6.5in) and 22.9cm (9in), were added to the tests. Crops were cut using an electric band saw.

4.2.4 Arrangement of crop samples in compression chambers

The arrangements of materials were categorized into two methods, parallel and random. Parallel arrangement means that all the stems were put horizontally in the same direction (Figure 4.5) and parallel to one of the sidewalls of the chamber.

Figure 4. 5. The materials were arranged horizontally in the same direction.

In addition to parallel arrangement, random arrangement was also used to compare the differences from parallel arrangement. The random arrangement in the thesis referred quasi-random. In this case, crop samples were randomly placed inside the chamber as shown in figure 4.6.

Figure 4. 6. The materials were arranged randomly.

4.3 Experimental facilities and measurements

4.3.1 Universal testing machine

The universal testing machine (Figure 4.7) was a product made by Cooper Instruments and Systems and used to compress energy crops in this study. The machine located in Agricultural and Biological Engineering building. The loading capacity of this machine was 89,000N (20,000lbf) which was limited by the maximum pressure of its hydraulic cylinders. Two identical hydraulic cylinders were in opposite direction to apply vertical loading force. The upper cylinder extends downward and the lower cylinder extends upward. Each cylinder could be controlled separately. The stroke of each cylinder was 25.4cm (10 inch). As the hydraulic system didn’t have a speed control valve. The hydraulic cylinders had a constant speed of 1.946cm/s (0.766 in/s) for all compression tests. The speed is not adjustable due to the design of the machine.

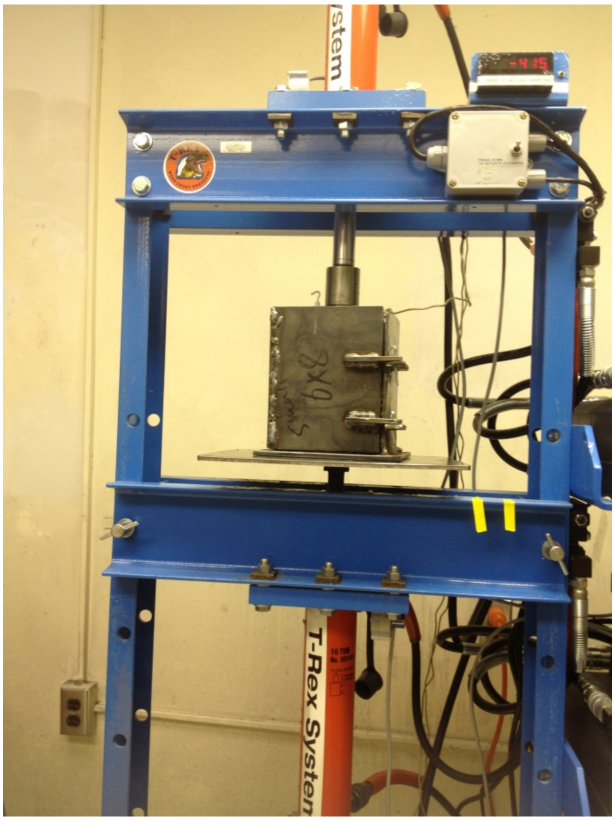


Figure 4. 7. The T-Rex machine compressing biomass.

There is a load cell mounted at the rod end of the upper cylinder. This load cell was connected to a data logger to record the loading process. Two potentiometers were also mounted on rod end of the cylinder to collect the vertical displacements of those two cylinders. The potentiometers are also connected to the data logger.

To perform the pre-loading progress precisely, a secondary load cell purchased from Transduce Techniques was mounted on to the compression system. The secondary load cell had a lower range (0-500 lbs.) in order to receive higher resolutions at lower vertical level. The low range load cell was placed manually between the top plate of the chamber and the rod end of upper cylinder each time. After all samples for this chamber was loaded into the chamber, this secondary load cell was removed and the main load cell will record the rest of compression process.

The universal testing machine could be operated manually or automatically. The manual operation was used in pre-loading stage. While in compression tests, the automatic operation was applied to maintain the consistency of measurements.

4.3.2 Measurements

All crop samples were weighed before loading them into the compression chamber in order to maintain the initial bulk density.

The starting density of loose switchgrass material was around 37-42kg/m^3. This starting density was obtained by arranging the loose material in the chamber gradually and applying an appropriate pre-load. The pre-loading process was also recorded as an initial compression process.

For loose corn material, the starting density was in a range of 41 to 43 kg/m^3.

Due to the relatively high plant density and large stem size, the initial density of Miscanthus was from 75 to 85kg/ m^3 for all parallel arrangements and 2-in (50 mm) long random arrangement. The starting density was between 40 and 45kg/m^3 in random arrangement treatments with long sizes (5.5in, 6.5in, 7.5in, 9in and 10in)

Moisture contents of the crop samples were determined using methods recommended in ASAE standards for forage (ASAE, 2003b). The average moisture content of switchgrass was 7.95±0.44% (w.b.). The average moisture content of October and December harvested corn stover were 19.62±4.02% (w.b.), and 21.02±2.81% (w.b.) respectively. The average moisture content of miscanthus was 11.2±0.55% (w.b.)

4.4 Experimental design

To obtain the relationships between sizes of chambers and specific energy consumption, two factors (crop and chamber size) were considered. Each factor had three levels evolved. Switchgrass, Mithcanthus, and Corn stover were selected due to their high potential to be uilized for energy souces in the U.S.

As shown in Table 4.1, the harvesting season, chamber size and particle size were considered as factors affecting energy consumption, and set as variables of the experiments. Each treatment was repeated five times and 120 tests in total.

Table 4. 1. Details of experimental design for Switchgrass.

	Chamber size	Particle size(cm)	Harvest time	Crop arrangement
1	I (smallest)	14.0	March 2014	Parallel
2	II	16.5	March 2014	Parallel
3	III	19.1	March 2014	Parallel
4	IV	22.9	March 2014	Parallel
5	V (largest)	25.4	March 2014	Parallel
6	I	14.0	October 2013	Parallel
7	III	19.1	October 2013	Parallel
8	V	25.4	October 2013	Parallel
9	I	14.0	March 2014	Random
10	II	16.5	March 2014	Random
11	III	19.1	March 2014	Random
12	IV	22.9	March 2014	Random
13	V	25.4	March 2014	Random
14	I	5.1	March 2014	Random
15	II	5.1	March 2014	Random
16	III	5.1	March 2014	Random
17	IV	5.1	March 2014	Random
18	V	5.1	March 2014	Random

Table 4. 2. Details of experimental design for Corn stover.

	Chamber size	Particle size(cm)	Harvest time	Crop arrangement
1	I (smallest)	14.0	October 2013	Parallel
2	III	19.1	October 2013	Parallel
3	V (largest)	25.4	October 2013	Parallel
4	I	5.1	October 2013	Random
5	III	5.1	October 2013	Random
6	V	5.1	October 2013	Random
7	I	14.0	December 2013	Parallel
8	III	19.1	December 2013	Parallel
9	V	25.4	December 2013	Parallel
10	I	5.1	December 2013	Random
11	III	5.1	December 2013	Random
12	V	5.1	December 2013	Random

Table 4. 3. Details of experimental design for Miscanthus.

	Chamber size	Particle size(cm)	Harvest time	Crop arrangement
1	I (smallest)	14.0	March 2014	Parallel
2	II	16.5	March 2014	Parallel
3	III	19.1	March 2014	Parallel
4	IV	22.9	March 2014	Parallel
5	V (largest)	25.4	March 2014	Parallel
6	I	14.0	March 2014	Random
7	II	16.5	March 2014	Random
8	III	19.1	March 2014	Random
9	IV	22.9	March 2014	Random
10	V	25.4	March 2014	Random
11	I	5.1	March 2014	Random
12	II	5.1	March 2014	Random
13	III	5.1	March 2014	Random
14	IV	5.1	March 2014	Random
15	V	5.1	March 2014	Random

4.5 Data collection and analysis

The data logger had a sampling rate of 16 data per second. Recorded data included time, displacement of the upper and the lower cylinders, vertical loading forces of two load cells over the course of each test. A LabVIEW program was used to program the data logger. Vertical displacement vs. loading force curve was plotted in Excel. If using the displacement as horizontal coordinate, the area under the vertical load would be the energy consumption. To reduce data fluctuation caused by the vibration during loading process, data sampling rate was reduced to 10 per second.

The calculation of energy consumption included both the preloading and loading processes. To access certain starting density of biomass, pre-loading was indispensable.

ANOVA was used to check the significant differences, and establish desired regression relationships between density and volume reduction.

Chapter 5 - Study of Switchgrass Compression

The study of switchgrass had 4 factors to be tested: chamber size, particle size, the arrangement method, and harvesting time. All the tests started with an approximate density of 40kg/m^3. Finally the compression process was stopped at 88% volume reduction. The specific energy consumptions were recorded. The detailed data are shown in Table 5.1.

Table 5. 1. Specific energy consumption of switchgrass at 60%, 70%, 80%, and 88% Volume reduction.

	Chamber	Particle length (cm)	Arrangement	Harvesting time	60% Volume reduction	70% Volume reduction	80% Volume reduction	88%Volume reduction
1	I	14.0	Parallel	March 2014	0.0965	0.2156	0.5817	1.9633
2	II	16.5	Parallel	March 2014	0.0590	0.1438	0.3941	1.6460
3	III	19.1	Parallel	March 2014	0.0841	0.2243	0.6612	2.0639
4	IV	22.9	Parallel	March 2014	0.0515	0.1255	0.3668	1.3896
5	V	25.4	Parallel	March 2014	0.0556	0.1844	0.5042	1.4270
6	I	14.0	Random	March 2014	0.1615	0.3116	0.6614	1.9256
7	II	16.5	Random	March 2014	0.1041	0.2264	0.5237	1.5552
8	III	19.1	Random	March 2014	0.1270	0.2612	0.5891	1.9011
9	IV	22.9	Random	March 2014	0.0988	0.2034	0.4608	1.4008
10	V	25.4	Random	March 2014	0.1098	0.2181	0.4837	1.4493
11	I	5.1	Random	March 2014	0.1188	0.2849	0.7578	2.0582
12	II	5.1	Random	March 2014	0.0647	0.1816	0.4611	1.5551
13	III	5.1	Random	March 2014	0.1092	0.2751	0.6954	2.1961
14	IV	5.1	Random	March 2014	0.1117	0.2568	0.6144	1.6539
15	V	5.1	Random	March 2014	0.1414	0.3101	0.7116	1.6720

5.1 The energy consumption using different sized chambers

The vertical compressing load vs. displacement data were processed to obtain the energy consumed during compression. Figure 5.1 and Figure 5.2 show examples of compression process. The black area in this figure is the energy consumption during compression. The energy consumption increases rapidly after the volume reduction reached to a level of 60-70%.

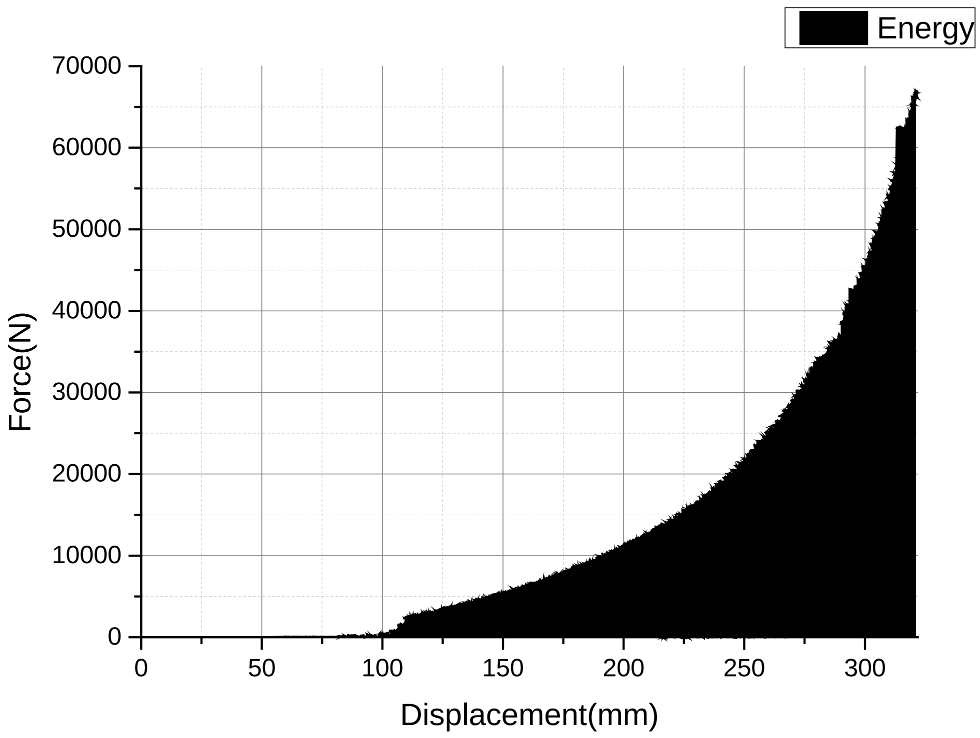


Figure 5. 1. Compression force vs. displacement graph (5.1cm miscanthus, Chamber V).

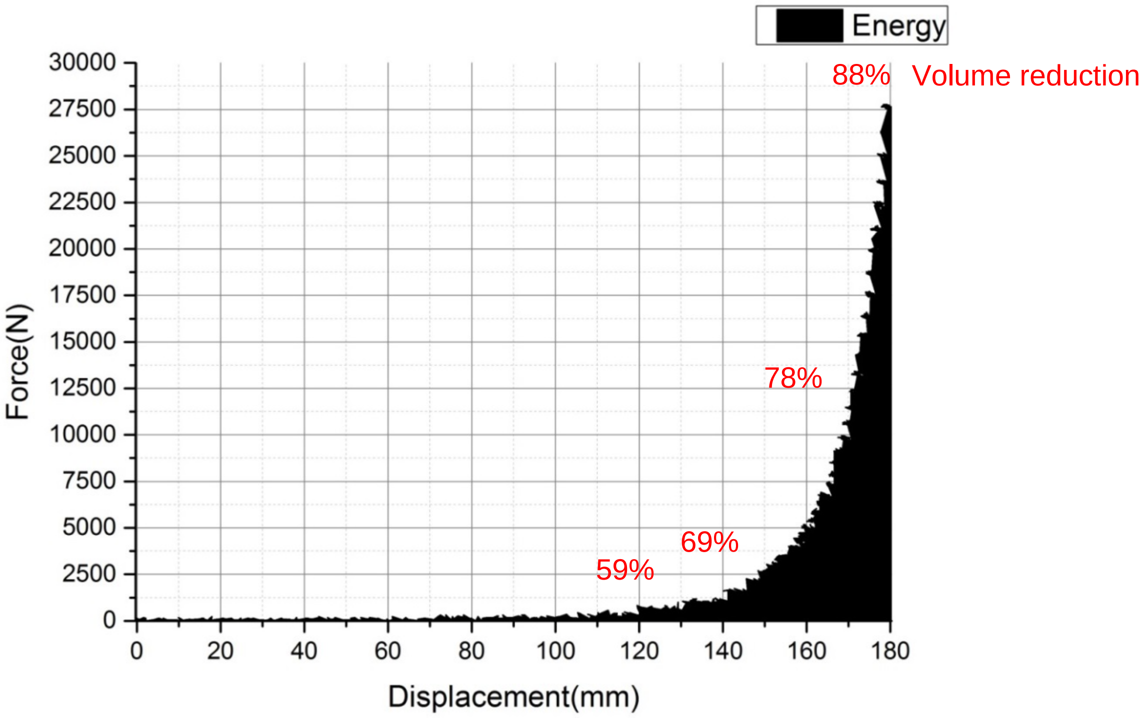


Figure 5. 2. Compression force vs. displacement graph (14cm switchgrass, Camber I).

The all experiments were distributed into 3 groups due to their different particle sizes and arrangement methods. Group 1 was the switchgrass with parallel arrangement and long particle size, Group 2 was with random arrangement method and long particle size, and the Group 3 was the biomass with random arrangement and 5.1cm particle size. The initial densities of all groups were around 40kg/m^3. The inter group comparison results at 88% volume reduction is shown in Table 5.2.

Table 5. 2. Specific energy consumption of switchgrass at 88% volume reduction.

Harvest time	Chamber	Particle size(cm)	Arrangement	Specific energy consumption(MJ/Mg)		Std.Dev.
March 2014	I	14.0	Parallel	1.9633	a	0.0779
March 2014	II	16.5	Parallel	1.6460	b	0.2284
March 2014	III	19.1	Parallel	2.0639	a	0.0434
March 2014	IV	22.9	Parallel	1.3896	c	0.1395
March 2014	V	25.4	Parallel	1.4270	bc	0.0439

Note: Means with the same letter are not significantly different from each other (Tukey HSD[a] test), and the mean difference is significant at the 0.05 level.

Harvest time	Chamber	Particle size(in)	Arrangement	Specific energy consumption(MJ/Mg)		Std.Dev.
March 2014	I	14.0	Random	1.9256	a	0.4431
March 2014	II	16.5	Random	1.5552	a	0.1329
March 2014	III	19.1	Random	1.9011	a	0.5024
March 2014	IV	22.9	Random	1.4512	a	0.0959
March 2014	V	25.4	Random	1.4493	a	0.1488

Note: Means with the same letter are not significantly different from each other (Tukey HSD[a] test), and the mean difference is significant at the 0.05 level.

Harvest time	Chamber	Particle size(in)	Arrangement	Specific energy consumption(MJ/Mg)		Std.Dev.
March 2014	I	5.1	Random	2.0582	a	0.0827
March 2014	II	5.1	Random	1.5551	b	0.3547
March 2014	III	5.1	Random	2.1961	a	0.0427
March 2014	IV	5.1	Random	1.6539	b	0.1324
March 2014	V	5.1	Random	1.6720	b	0.0690

Note: Means with the same letter are not significantly different from each other (Tukey HSD[a] test), and the mean difference is significant at the 0.05 level.

The results above indicate that the size of chamber does have impact on specific energy consumption. The increasing of chamber size decreases the specific energy consumption in Group 1 and Group 3. However, this effect is not significant (α =0.05) for Group 2.

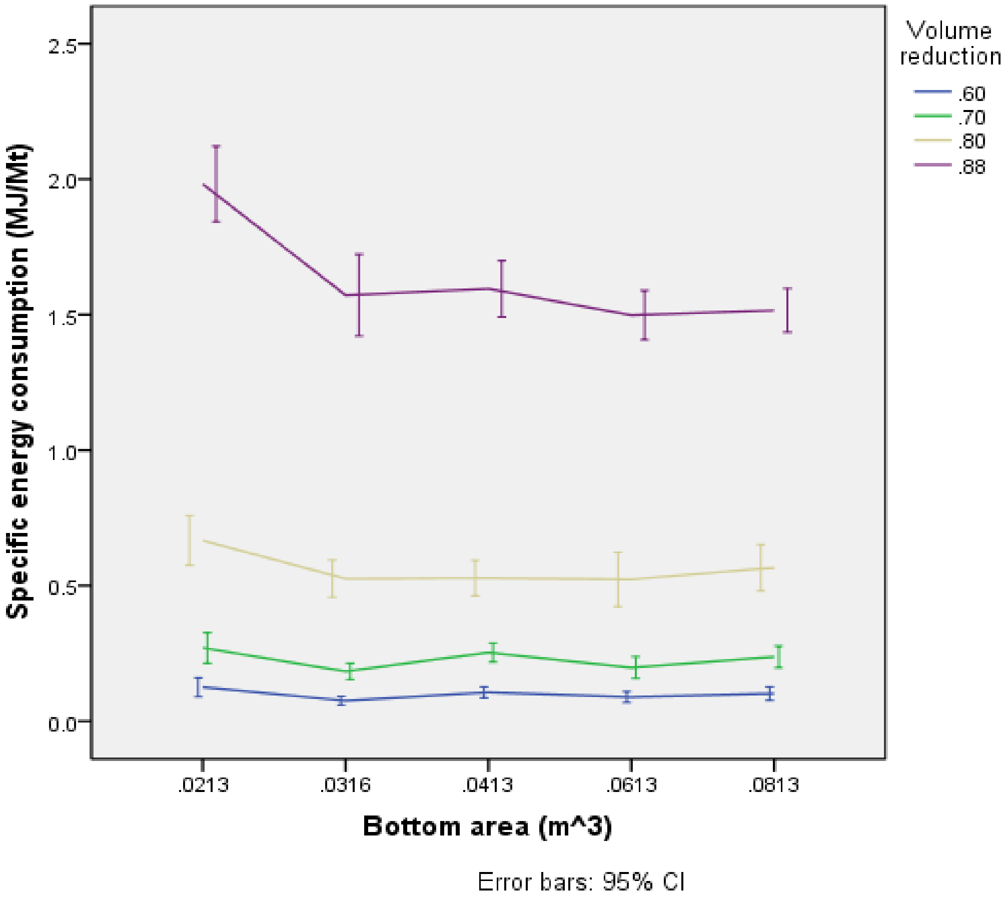


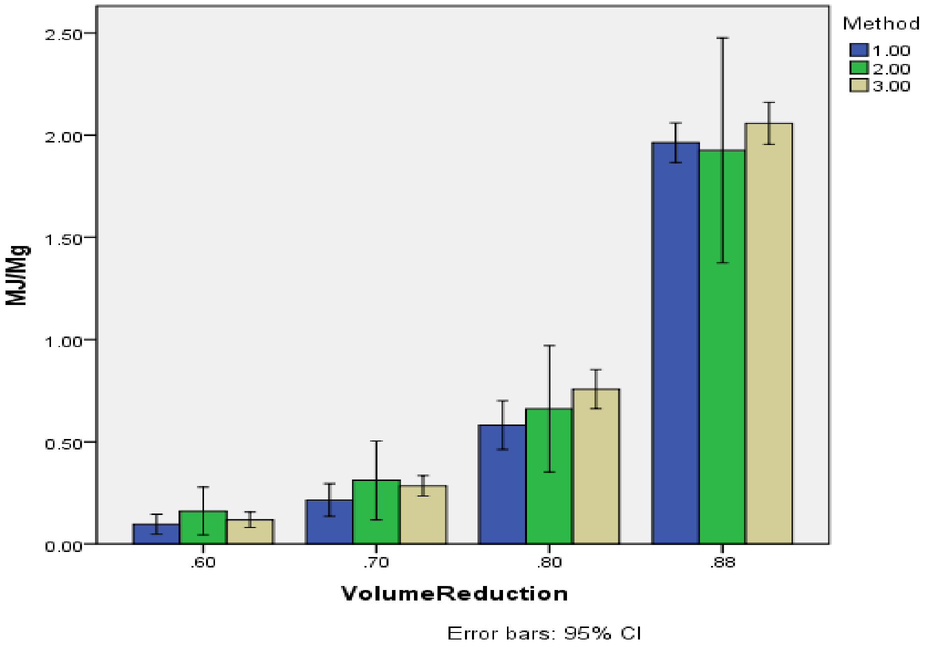
Figure 5. 3. Specific energy consumption (MJ/Mg) graph of switchgrass compressed in five different size chambers.

Figure 5.3 indicated that the energy consumption decreased with increase size of chamber. The curve became flat after Chamber II (0.316m^3). And the higher volume reduction caused larger energy consumption decrease.

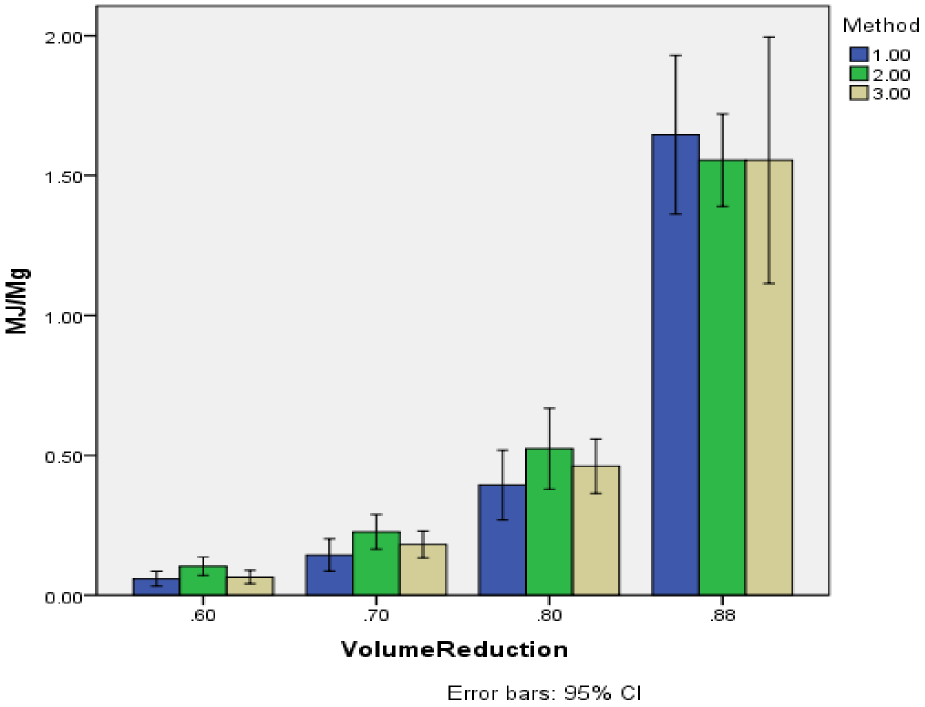
5.2 Comparison between the arrangement and particle size

With the same particle size, two arrangement methods parallel and random were compared random. Under the same random arrangement, long particle size and 2-inch particle size were also compared. The result is shown as following (Figure 5.4). Colors blue, green, and yellow stand for Group 1, 2, and 3, respectively. 95% CI stands for 95% confidence interval. 0.6, 0.7, 0.8, and 0.88 stand for 60%, 70%, 80%, and 88% volume reduction.

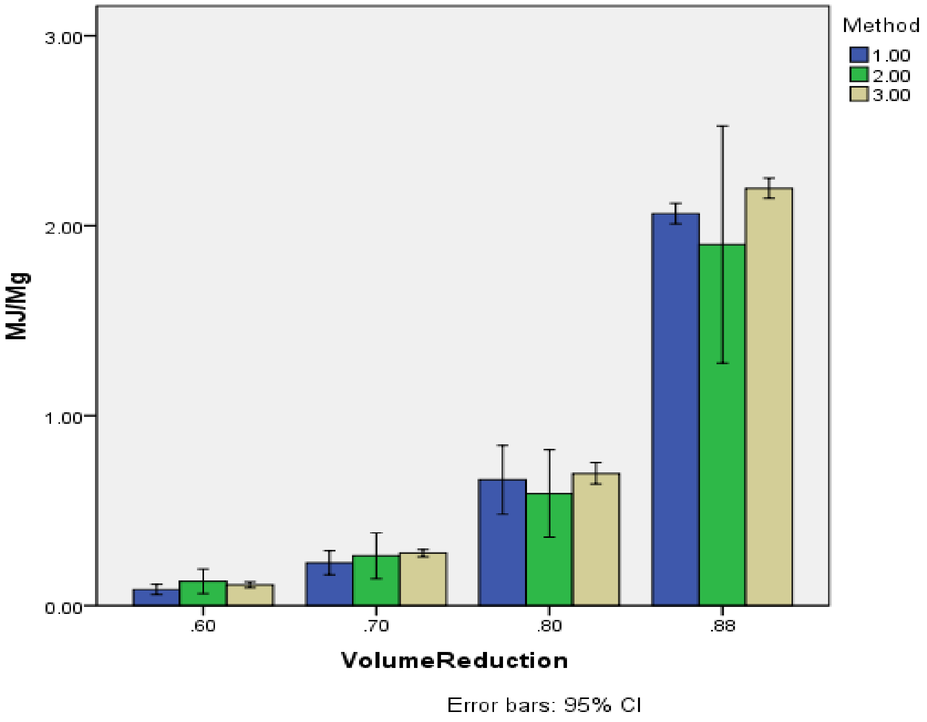
Chamber I (Length x Width x Height: 15.2cm x14cm x 20.3cm)



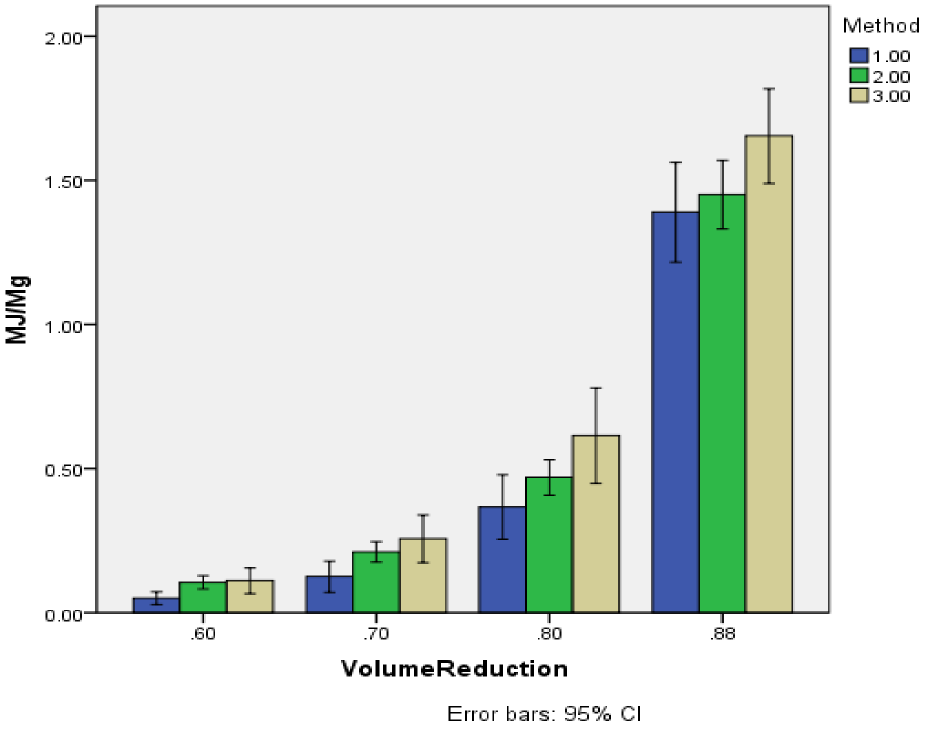
Chamber II (Length x Width x Height: 17.8cm x17.8cm x 24.1cm)



Chamber III (Length x Width x Height: 20.3cm x20.3cm x 27.9cm)



Chamber IV (Length x Width x Height: 25.4cm x25.1cm x 31.8cm)



Chamber V (Length x Width x Height: 30.5cm x26.7cm x 40.6cm)

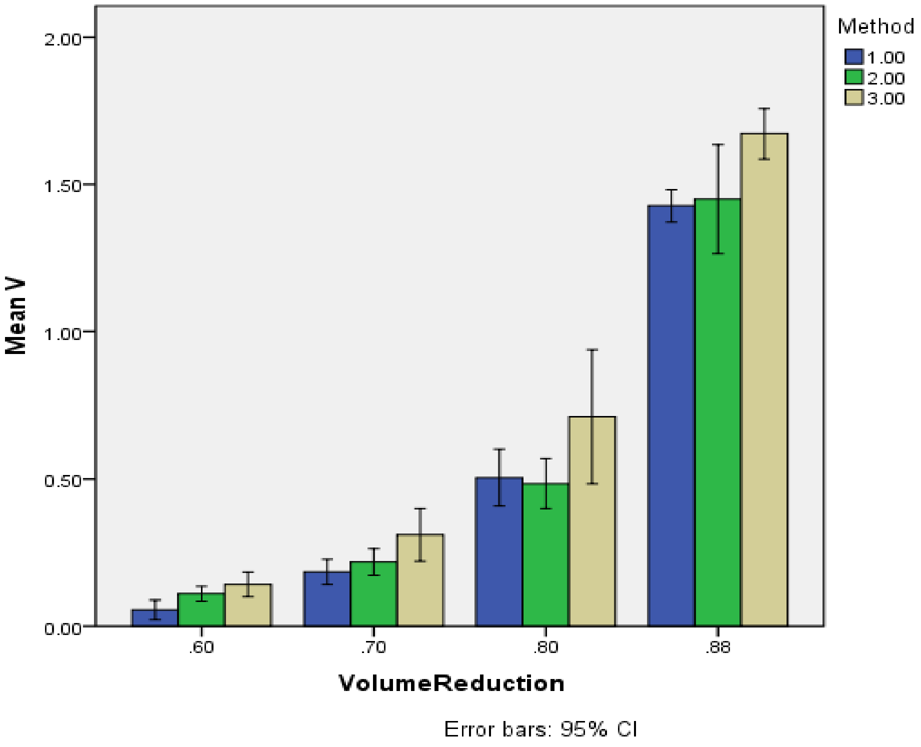


Figure 5. 4. Comparison of switchgrass between the arrangement and particle size.

The Figure 5.4 indicates that the parallel arrangement method resulted in less energy consumption than random arrangement. Shorter particle also increased the energy consumption during compression; but, both factors didn't impact the energy consumption significantly.

5.3 A case study of seasonal difference

Fall 2013 harvested switchgrass with Chambers I, III, and V were compared with spring 2014 harvested switchgrass (Table 5.3). The Chambers I and III had no significant differences (α =0.05) on the aspect of specific energy consumption. However, the Chamber V could significantly decrease the energy consumption (α =0.05).

Table 5. 3. Specific energy consumption of 2013 harvested switchgrass at 88% volume reduction.

Harvest time	Chamber	Particle size(cm)	Arrangement	Specific energy consumption(MJ/Mg)		Std.Dev.
Fall 2013	I	14.0	parallel	1.8517	a	0.0408
Fall 2013	III	19.1	parallel	1.6594	a	0.0403
Fall 2013	V	25.4	parallel	1.3235	b	0.0509

Note: Means with the same letter are not significantly different from each other (Tukey HSD[a] test), and the mean difference is significant at the 0.05 level.

In Figure 5.5, colors blue stands for fall 2013 harvested switchgrass and green stands for spring 2014 harvested switchgrass. 95% CI stands for 95% confidence interval. 0.6, 0.7, 0.8, and 0.88 stand for 60%, 70%, 80%, and 88% volume reduction.

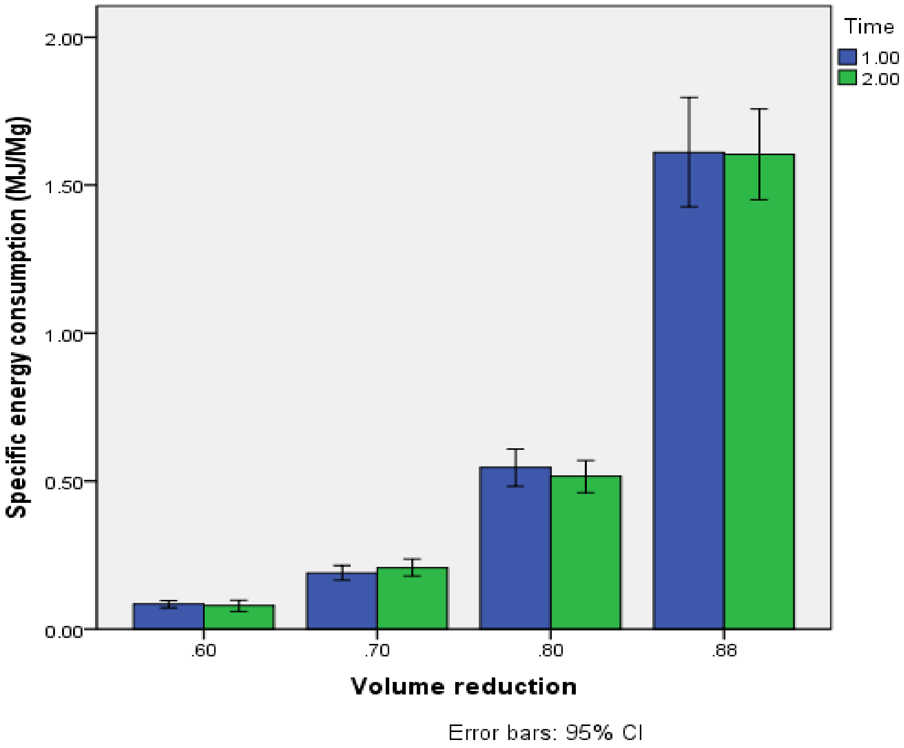


Figure 5. 5. Compression energy consumption comparison between spring 2014 and fall 2013 harvested switchgrass.

The moisture contents of spring 2014 and fall 2013 harvested crops were all between 8% and 10%. The graph (Figure5.7) shows that the difference of energy consumption became more obvious when increasing the volume reduce; but, when the moisture contents were very similar, the season won’t impact compression specific energy consumption.

Chapter 6 - Study of Corn Stover Compression

Two adjacent corn fields were selected to collect stove samples in this study. Both these fields have the similar soil, illumination, and weather conditions. The only difference was that one field was combined in October 2013, and the other one was combined in December 2013. Both of the fields were covered by snow from October to December. For the field combined in December, corn plants were standing in the field; but the field combined in October corn stover had two months laid under the snow.

Table 6. 1. Specific energy (MJ/Mg) consumption of corn stover at 60%, 70%, 80%, and 88% Volume reduction.

	Chamber	Particle length (cm)	Arrangement	Harvesting time	60% Volume reduction	70% Volume reduction	80% Volume reduction	88%Volume reduction
1	I	14.0	Parallel	Oct. 2013	0.0901	0.2017	0.4983	2.0008
2	III	19.1	Parallel	Oct. 2013	0.1666	0.3371	0.7052	2.3315
3	V	25.4	Parallel	Oct. 2013	0.0764	0.1627	0.3658	1.1294
4	I	5.1	Random	Oct. 2013	0.2395	0.5113	1.0848	2.0255
5	III	5.1	Random	Oct. 2013	0.1907	0.3914	0.8345	2.5520
6	V	5.1	Random	Oct. 2013	0.0707	0.1533	0.3482	1.2960
7	I	14.0	Parallel	Dec. 2013	0.0316	0.0870	0.2770	1.7201
8	III	19.1	Parallel	Dec. 2013	0.0698	0.1618	0.3932	1.8910
9	V	25.4	Parallel	Dec. 2013	0.1136	0.2383	0.5015	1.6596
10	I	5.1	Random	Dec. 2013	0.1174	0.2434	0.5184	1.4930
11	III	5.1	Random	Dec. 2013	0.0692	0.1611	0.3805	1.8412
12	V	5.1	Random	Dec. 2013	0.0641	0.0506	0.3284	1.4482

6.1 The energy consumption study using different sized chambers

October and December harvested corn stovers were used in this study. All tests were distributed into two groups. Group 1 was the corn stover with parallel arrangement and long particle size, Group 2 was the biomass with random arrangement and 2-in long particle size. The initial densities of all groups were around 40kg/m^3. Different with switchgrass, the graphs below indicated that the corn stover compressions don’t have significantly differences between different chambers (Figures 6.1-6.4).

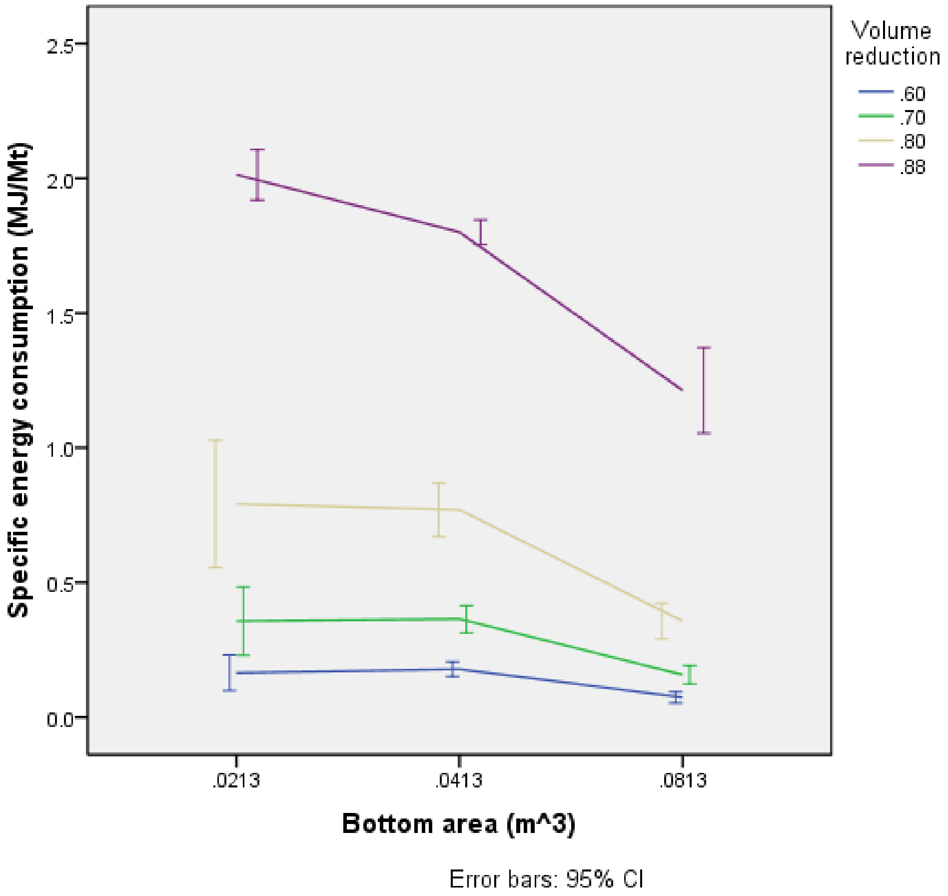


Figure 6. 1. Specific energy consumption (MJ/Mg) graph of Oct. harvested corn stover compressed in five different size chambers.

Figure 6.1 indicated that the energy consumption was less by using larger size compression chamber for Oct. harvested corn stover. The decrease of energy consumption became more obviously when the volume reduction was high.

Compared to Oct. harvested corn stover, the Dec. combined corn stover had less variation when the size of chamber was changed. The curves (Figure 6.2) are basically in the horizontal level.

In sum, the harvested time could impact the effect of chamber size on energy consumption.

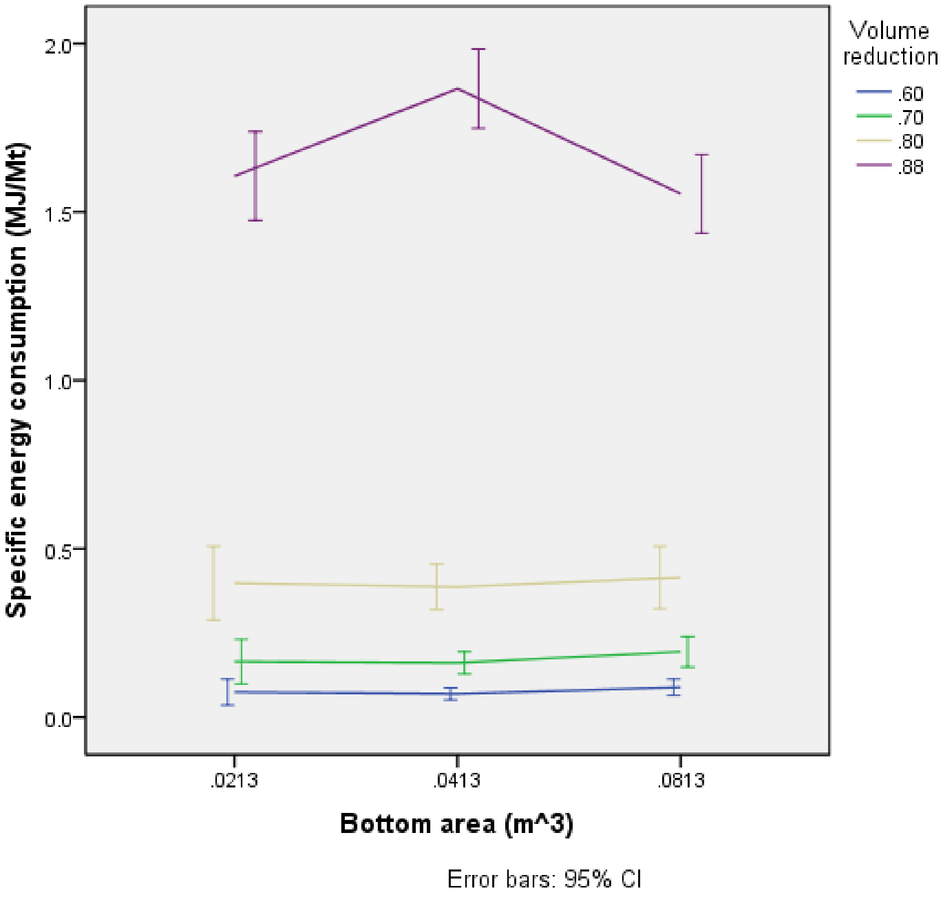


Figure 6. 2. Specific energy consumption (MJ/Mg) graph of Dec. harvested corn stover compressed in five different size chambers.

6.2 Comparison between the arrangement and particle size

The corn stovers were divided into two groups. Group 1 (blue bar) stands for the parallel stem with longer biomass particle, and Group 2 (green bar) stands for random arrangement with 2-inch particle. The Figure 6.3 shows that the stem with parallel arrangement method could decrease the energy consumption, but not significantly. The residuals of corn contain stovers, leaves, roots, and rods, which leaded the form of residual complicated. It is hard to arrange the corn stover into a certain method. Group 2 has higher energy consumption because of the shorter particle size. The shorter length leaded the particles harder to be compressed. 95% CI stands for 95% confidence interval. 0.6, 0.7, 0.8, and 0.88 stand for 60%, 70%, 80%, and 88% volume reduction.

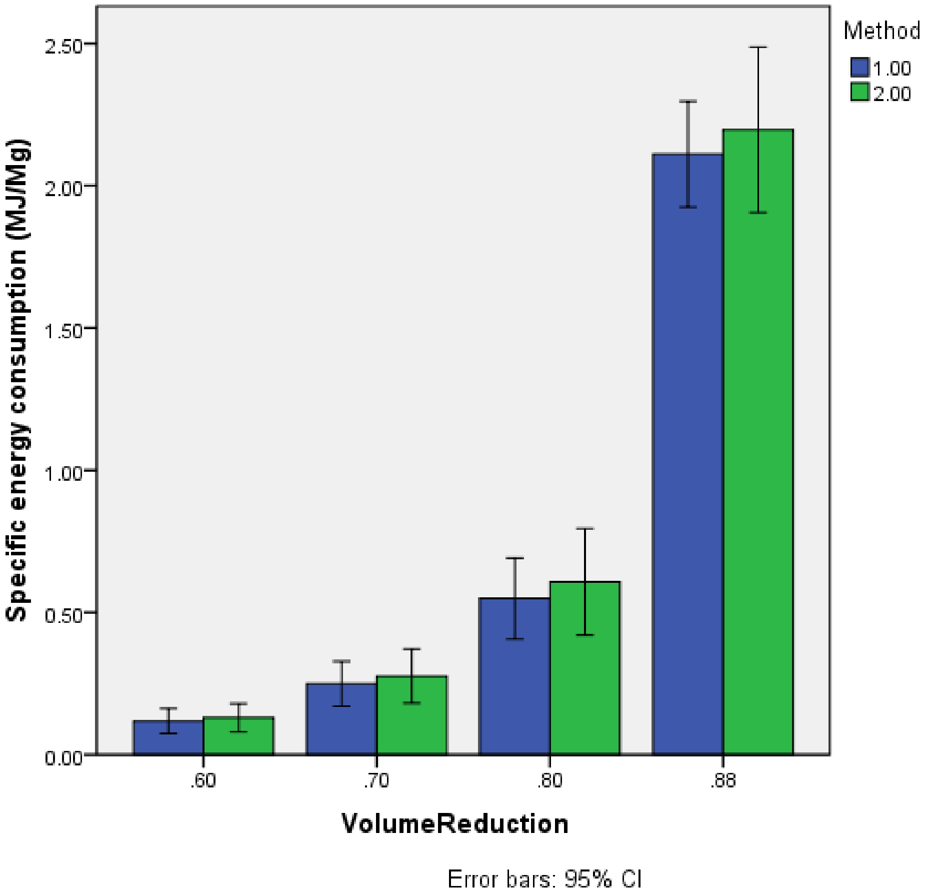


Figure 6. 3. The comparison between particle sizes and arrangement methods (Mean of five chamber size, Miscanthus).

6.3 A comparison of compression energy consumption between October and December harvested corn.

The data were collected from corn stovers which were planned on two neighbor corn fields. Field A was combined in October 2013, and Field B was combined December 2014. The Field A has two months covered by snow. The comparing results are shown as following in Figure 6.4. The blue bars stand for Oct. combined corn stover, and the green ones stand for Dec. combined corn stover. 95% CI stands for 95% confidence interval. 0.6, 0.7, 0.8, and 0.88 stand for 60%, 70%, 80%, and 88% volume reduction.

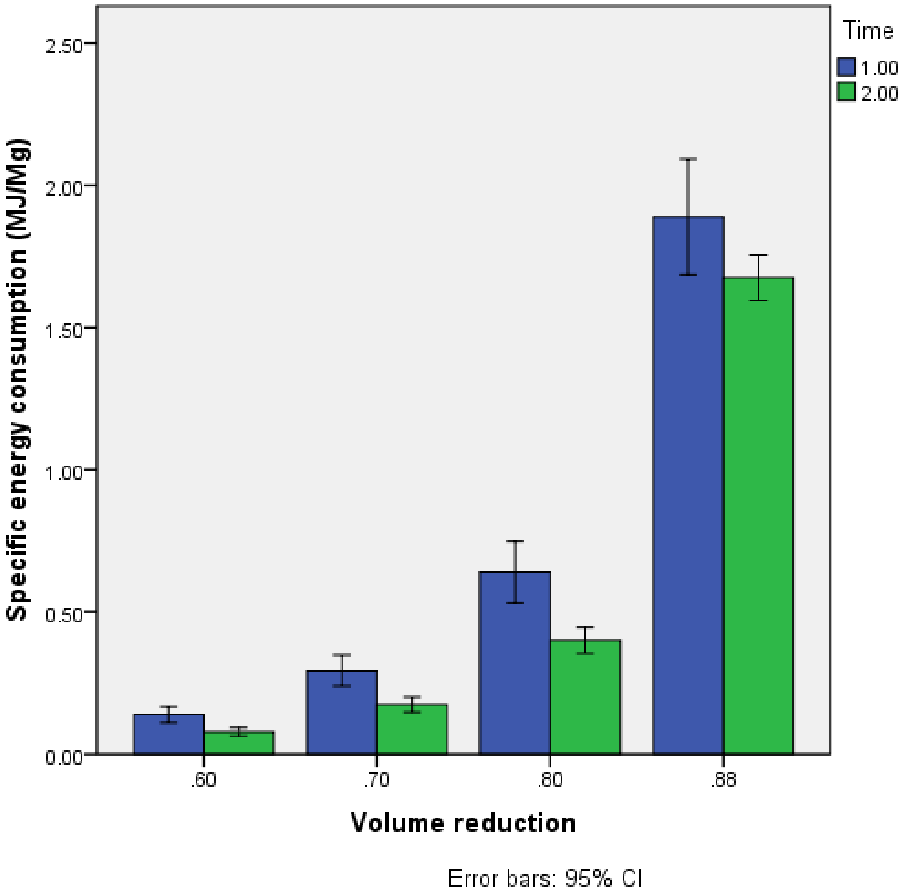


Figure 6. 4. The comparison between two harvested time corn stover (Mean of Chamber I, III, IV).

The results indicated that the Dec. combined corn stover significantly decreased the energy consumption. However, the increasing volume reduction decreased the difference. Additional two months under snow condition made the stovers, leaves, and rods softer, which could save energy consumption in compression.

Chapter 7 - Study of Miscanthus Compression

In the experiments of miscanthus, chamber size, particle size, and arrangement method were the factors to be tested. Due to the hardness of miscanthus and the capacity of the compressor, the limitation of volume reduction was set at 80%. The results of energy consumption are shown as following in Table 7.1.

Table 7. 1. Specific energy consumption (MJ/Mg) of miscanthus at 50%, 60%, 70%, and 80% Volume reduction.

	Chamber	Particle length (cm)	Arrangement	Harvesting time	50% Volume reduction	60% Volume reduction	70% Volume reduction	80%Volume reduction
1	I	14.0	Parallel	March 2014	0.2001	0.5081	1.2450	2.0885
2	II	16.5	Parallel	March 2014	0.0750	0.2459	0.6482	1.6837
3	III	19.1	Parallel	March 2014	0.1294	0.3297	0.7690	1.7223
4	IV	22.9	Parallel	March 2014	0.0515	0.1564	0.4385	1.2061
5	V	25.4	Parallel	March 2014	0.1081	0.2844	0.6753	1.2271
6	I	14.0	Random	March 2014	0.1278	0.3281	0.7018	1.4560
7	II	16.5	Random	March 2014	0.0790	0.2398	0.5017	1.0882
8	III	19.1	Random	March 2014	0.2454	0.4313	0.7417	1.3489
9	IV	22.9	Random	March 2014	0.0720	0.1559	0.3268	0.7848
10	V	25.4	Random	March 2014	0.1258	0.2379	0.4148	0.8063
11	I	5.1	Random	March 2014	0.3520	0.6433	1.1845	2.2541
12	II	5.1	Random	March 2014	0.3474	0.6744	1.1857	2.1301
13	III	5.1	Random	March 2014	0.2766	0.5369	0.9986	1.9007
14	IV	5.1	Random	March 2014	0.2033	0.4313	0.8532	1.6680
15	V	5.1	Random	March 2014	0.2147	0.4662	0.9251	1.6087

7.1 The energy study of different size chamber

The all 15 treatments were divided into 3 groups due to their different particle sizes and arrangement methods. Group 1 was the miscanthus with parallel arrangement and long particle size, Group 2 was with random arrangement method and long particle size, and the Group 3 was the biomass with random arrangement and 5.1cm long particle size. The initial densities of Groups 2 and 3 were around 40kg/m^3. However, the initial density of Group 1 was about 80kg/m^3 because of the smaller gap between the particles. The inter group comparison results at 80% volume reduction is shown is Table 7.1.

Table 7. 2. Specific energy consumption (MJ/Mg) of miscanthus at 80% volume reduction.

Harvest time	Chamber	Particle size(cm)	Arrangement	Specific energy consumption(MJ/Mg)		Std.Dev.
March 2014	I	14.0	Parallel	2.0885	a	0.095
March 2014	II	16.5	Parallel	1.6837	a	0.3901
March 2014	III	19.1	Parallel	1.7223	a	0.3343
March 2014	IV	22.9	Parallel	1.2061	b	0.0997
March 2014	V	25.4	Parallel	1.2271	b	0.0842

Note: Means with the same letter are not significantly different from each other (Tukey HSD[a] test), and the mean difference is significant at the 0.05 level.

Harvest time	Chamber	Particle size(cm)	Arrangement	Specific energy consumption(MJ/Mg)		Std.Dev.
March 2014	I	14.0	Random	1.4560	a	0.3594
March 2014	II	16.5	Random	1.0882	ab	0.2397
March 2014	III	19.1	Random	1.3489	a	0.348
March 2014	IV	22.9	Random	0.7848	b	0.0675
March 2014	V	25.4	Random	0.8063	b	0.1494

Note: Means with the same letter are not significantly different from each other (Tukey HSD[a] test), and the mean difference is significant at the 0.05 level.

Harvest time	Chamber	Particle size(cm)	Arrangement	Specific energy consumption(MJ/Mg)		Std.Dev.
March 2014	I	5.1	Random	2.2541	a	0.0921
March 2014	II	5.1	Random	2.1301	a	0.2819
March 2014	III	5.1	Random	1.9007	ab	0.2351
March 2014	IV	5.1	Random	1.6680	b	0.0901
March 2014	V	5.1	Random	1.6087	b	0.1757

Note: Means with the same letter are not significantly different from each other (Tukey HSD[a] test), and the mean difference is significant at the 0.05 level.

The results show that the specific energy consumption decreases with increasing chamber size. There is no significant ($\alpha=0.05$) difference between adjacent chamber sizes; however, the Chamber I, II are significantly different from Chamber IV, V ($\alpha=0.05$).

To analysis the detailed relationships of energy consumption between the chambers, 3 line charts are drawn as follows. (Figure 7.1, Figure 7.2, Figure 7.3)

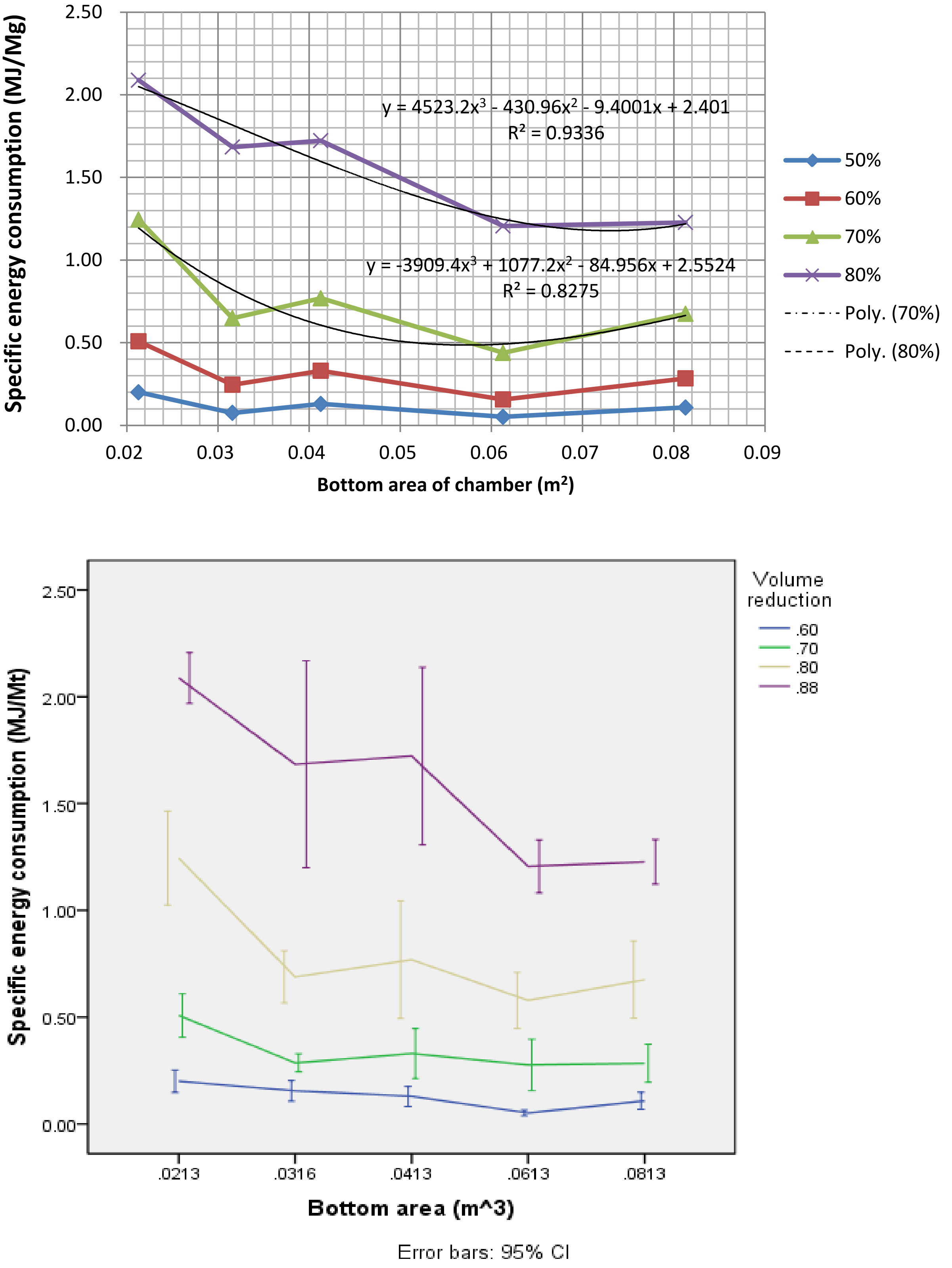


Figure 7. 1. Specific energy consumption (MJ/Mg) graph of parallel long miscanthus particle compressed in five different size chambers (Group1).

The 70% volume reduction curve can be fit with equation:

$$y = -3909.4x^3 + 1077.2x^2 - 84.956x + 2.5524 \ (R^2 = 0.8275)$$

y is specific energy consumption (MJ/Mg)

x is bottom area of chamber (m^3)

The 80% volume reduction curve can be fit with equation:

$$y = 4523.2x^3 - 430.96x^2 - 9.4001x + 2.401 \ (R^2 = 0.9336)$$

y is specific energy consumption (MJ/Mg)

x is bottom area of chamber (m^3)

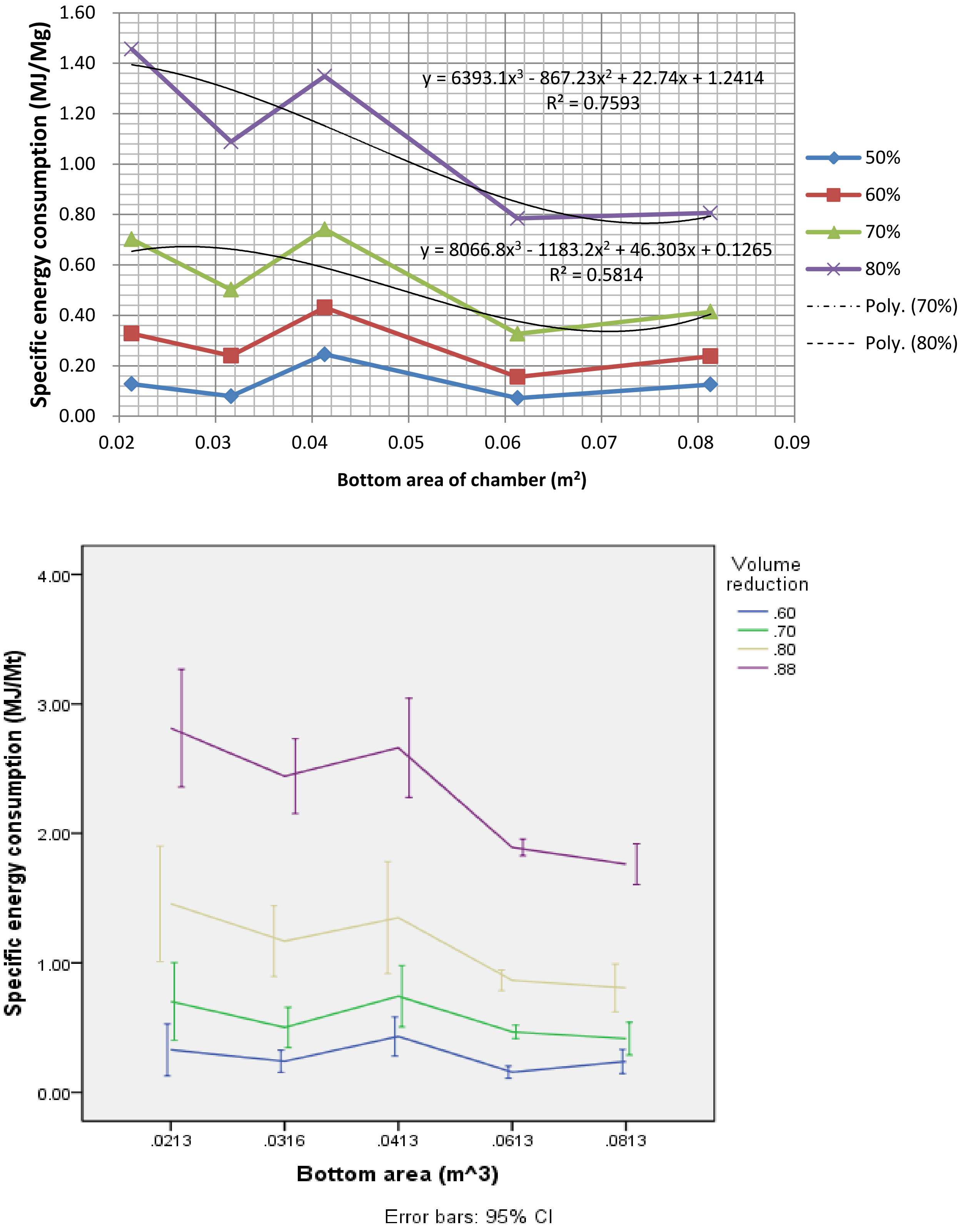


Figure 7. 2. Specific energy consumption (MJ/Mg) graph of random long miscanthus particle compressed in five different size chambers (Group2).

The 70% volume reduction curve can be fit with equation:

$$y = 8066.8x^3 - 1183.2x^2 + 46.303x + 0.1265 \quad (R^2 = 0.5814)$$

y is specific energy consumption (MJ/Mg)

x is bottom area of chamber (m^3)

The 80% volume reduction curve can be fit with equation:

$$y = 6393.1x^3 - 867.23x^2 + 22.74x + 1.2414 \quad (R^2 = 0.7593)$$

y is specific energy consumption (MJ/Mg)

x is bottom area of chamber (m^3)

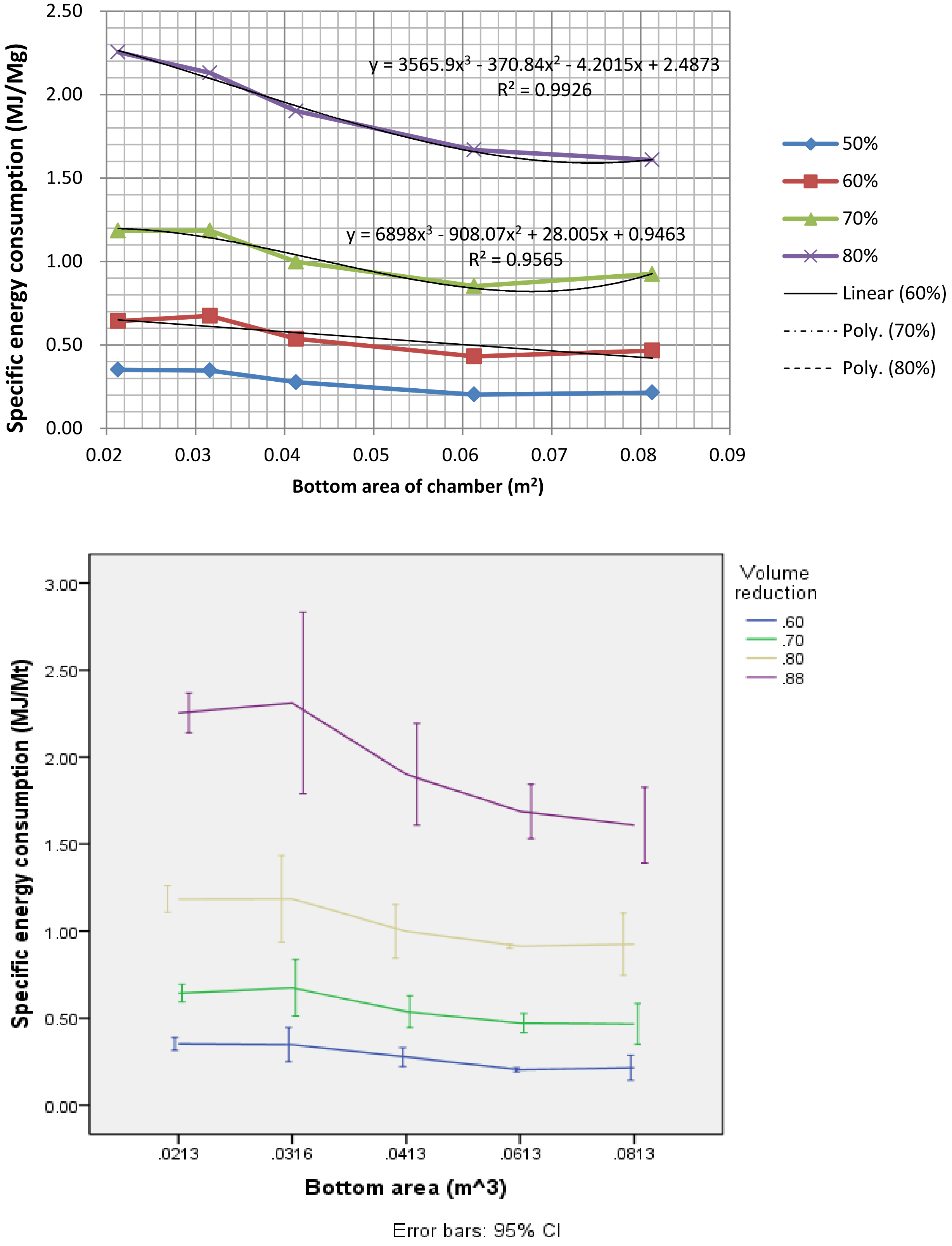


Figure 7. 3. Specific energy consumption (MJ/Mg) graph of random 2-inch miscanthus particle compressed in five different size chambers (Group3).

The 70% volume reduction curve can be fit with equation:

$$y = 6898x^3 - 908.07x^2 + 28.005x + 0.9463 \quad (R^2 = 0.9565)$$

y is specific energy consumption (MJ/Mg)
x is bottom area of chamber (m^3)

The 80% volume reduction curve can be fit with equation:

$$y = 3565.9x^3 - 370.84x^2 - 4.2015x + 2.4873 \quad (R^2 = 0.9926)$$

y is specific energy consumption (MJ/Mg)
x is bottom area of chamber (m^3)

The higher volume reduction will cause a sharper curve, which means the effect from chamber size will come more obviously when the volume reduction comes high.

7.2 Comparison of the arrangement and particle size

To achieve the same percentage of volume reduction, 5.1-cm long particle with random arrangement had the highest specific energy consumption. The long particle size with random arrangement method had the lowest value of energy consumption. The trend of this difference became more significant when increasing volume reduction (Figure 7.4). Colors blue, green, and yellow stand for Group 1, 2, and 3, respectively. 95% CI stands for 95% confidence interval. 0.6, 0.7, 0.8, and 0.88 stand for 60%, 70%, 80%, and 88% volume reduction.

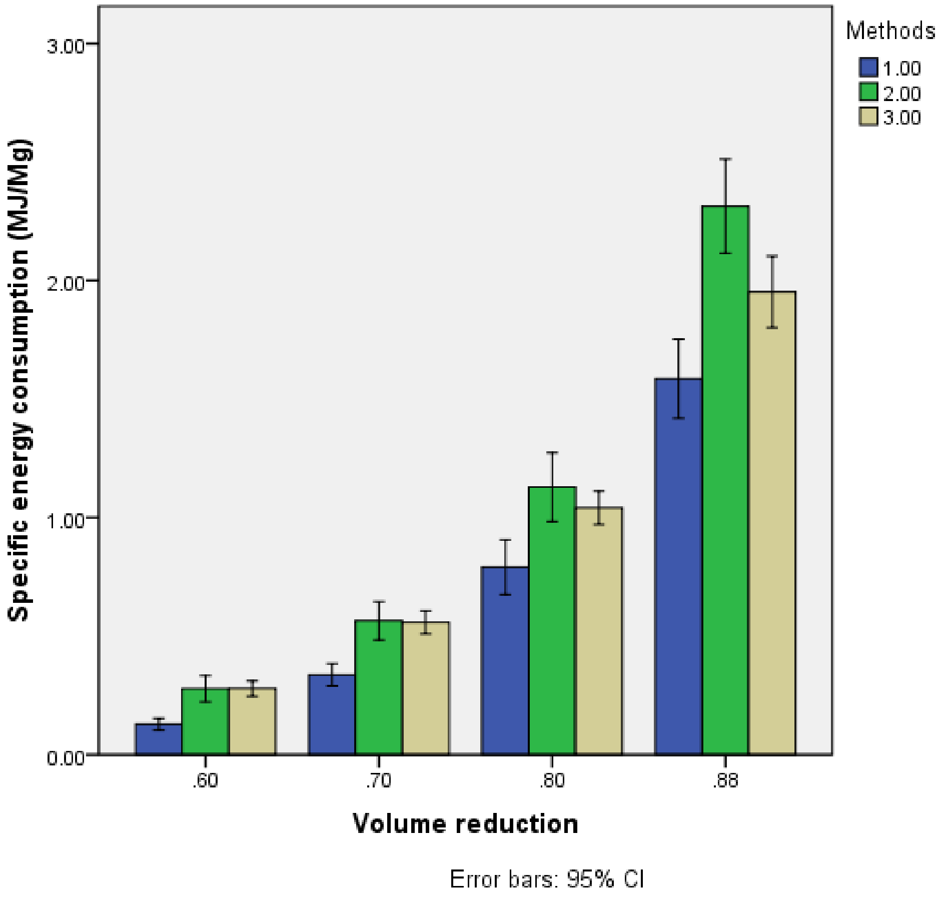


Figure 7. 4. The effect from arrangement and particle size on miscanthus compression (1, 2, 3 in legend stand for Groups 1, 2, 3 respectively).

The Figure 7.4 indicates that the parallel arrangement significant reduce the energy consumption. Each group of three bars shows the specific energy needed to compress those three groups to the same final density. When the miscanthus was arranged in the same direction (parallel, Group 1), it required significantly lower specific energy compared to the other two groups. Also, it is easy to obtain a 80kg/m^3 initial density which is exactly as twice as the density of Group 2. However, the parallel arrangement may cause a higher horizontal pressure on the side walls because stem lateral sliding may happen during compression.

The shorter biomass length decreases the energy consumption; but it is not significant. The Group 3 also had a relatively high initial density which was 80kg/m^3. But the shorter length is also led the particle harder to be compressed. These can be seen from results in Group 3, which has higher energy consumption than that of Group1; but it is lower than Group 2.

In real production, using a machine to compress miscanthus may decrease the energy consumption if a parallel arrangement can be achieved. The stronger sidewall pressure may require a stronger structure for the baler.

Chapter 8 - Comparison between crops and suggested compression volume reduction

8.1 Comparison of compression specific energy consumption between crops

Since the compression initial densities were different, the density (kg/m^3) of biomass should be used as a reference benchmark instead of using percentage of volume reduction. Long particle size biomass with parallel arrangement methods are compared as follows (Table 8.1). The density 160kg/m^3, 200kg/m^3, 267kg/m^3, 400kg/m^3 corresponded the 60%, 70%, 80%, and 88% volume reduction. The result showed that three crops are close to each other.

Table 8. 1. Specific energy consumption (MJ/Mg) comparison between switchgrass, corn stover, and miscanthus.

	Crops	Chamber	Particle length (cm)	Arrangement	160kg/m3	200kg/m3	267kg/m3	400kg/m3
1	Switchgrass	I	14.0	Parallel	0.3732	0.5817	1.1444	1.9633
2	Corn stover	I	14.0	Parallel	0.3173	0.4983	0.9030	2.0008
3	Miscanthus	I	14.0	Parallel	0.2001	0.5081	1.2450	2.0885
4	Switchgrass	III	19.1	Parallel	0.3748	0.6612	1.3189	2.0639
5	Corn stover	III	19.1	Parallel	0.3598	0.7052	0.9422	2.3315
6	Miscanthus	III	19.1	Parallel	0.1294	0.3297	0.7690	1.7223
7	Switchgrass	V	25.4	Parallel	0.3054	0.5042	0.9578	1.4270
8	Corn stover	V	25.4	Parallel	0.2378	0.3658	0.5898	1.1294
9	Miscanthus	V	25.4	Parallel	0.1081	0.2844	0.6753	1.2271

8.2 Suggested compression volume reduction

Using energy consumption (J) as the vertical axis, and then the energy consumption vs. displacement graph could be drawn as shown in Figure 8.1. In this graph, a 45 degree tangent line was applied to determine the critical point. The critical point indicates that the compression force will increase at a much higher rate compared to the rate of bulk density increases. For the example shown in Figure 8.1, the critical point is 63.1% volume reduction. After this point, it means that to obtain per 1mm compression displacement more than 1 J will be used. In other word, 63.1% is a suggested volume reduction for this case.

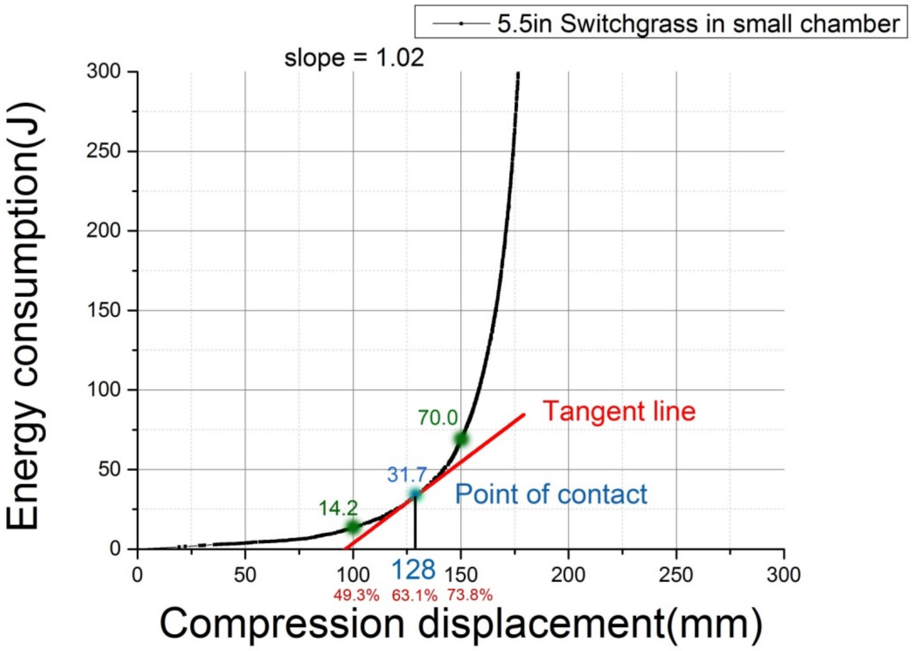


Figure 8. 1. Energy consumption vs. displacement graph of 14cm switchgrass in a small camber (15.2cm x14cm x20.3cm)

Table 8. 2. Suggested Volume reduction & Specific energy consumption.

Crops	Harvest time	Chamber size	Particle length (cm)	Arrangement	Volume reduction (%)	Std.Dev.	Specific energy consumption (MJ/t)	Std.Dev.
Switchgrass	Mar.2014	I	14.0	parallel	63.72	1.01	0.1455	0.0197
	Mar.2014	III	19.1	parallel	57	2.90	0.0606	0.0023
	Mar.2014	V	25.4	parallel	51.56	3.30	0.0314	0.0028
	Mar.2014	I	5.1	random	60.6	1.06	0.1265	0.0288
	Mar.2014	III	5.1	random	54.5	3.02	0.0599	0.0062
	Mar.2014	V	5.1	random	42.88	2.55	0.0271	0.0021
Corn stover	Oct.2013	I	14.0	parallel	65.62	2.58	0.1360	0.0343
	Oct.2013	III	19.1	parallel	49.3	3.76	0.0745	0.0066
	Oct.2013	V	25.4	parallel	51.38	4.56	0.0370	0.0141
	Oct.2013	I	5.1	random	53.38	4.15	0.1543	0.0128
	Oct.2013	III	5.1	random	46.62	2.27	0.0656	0.0062
	Oct.2013	V	5.1	random	52.84	4.04	0.0390	0.0050
	Dec. 2013	I	14.0	parallel	72.02	3.78	0.1039	0.0325
	Dec. 2013	III	19.1	parallel	61.12	2.94	0.0717	0.0067
	Dec.2013	V	25.4	parallel	44.38	2.79	0.0364	0.0027
	Dec. 2013	I	5.1	random	63.94	2.25	0.1643	0.0217
	Dec. 2013	III	5.1	random	60.32	3.57	0.0692	0.0126
	Dec. 2013	V	5.1	random	53.82	4.94	0.0352	0.0050
Miscanthus	Mar.2014	I	14.0	parallel	37.04	3.85	0.0099	0.0033
	Mar.2014	III	19.1	parallel	35.70	1.68	0.0118	0.0035
	Mar.2014	V	25.4	parallel	30.96	3.02	0.0187	0.0052
	Mar.2014	I	14.0	random	46.66	5.55	0.0100	0.0018
	Mar.2014	III	19.1	random	34.78	4.29	0.0143	0.0050
	Mar.2014	V	25.4	random	34.74	6.35	0.0237	0.0047
	Mar.2014	I	5.1	random	29.72	1.93	0.0086	0.0027
	Mar.2014	III	5.1	random	26.20	1.35	0.0078	0.0015
	Mar.2014	V	5.1	random	30.14	3.15	0.0113	0.0030

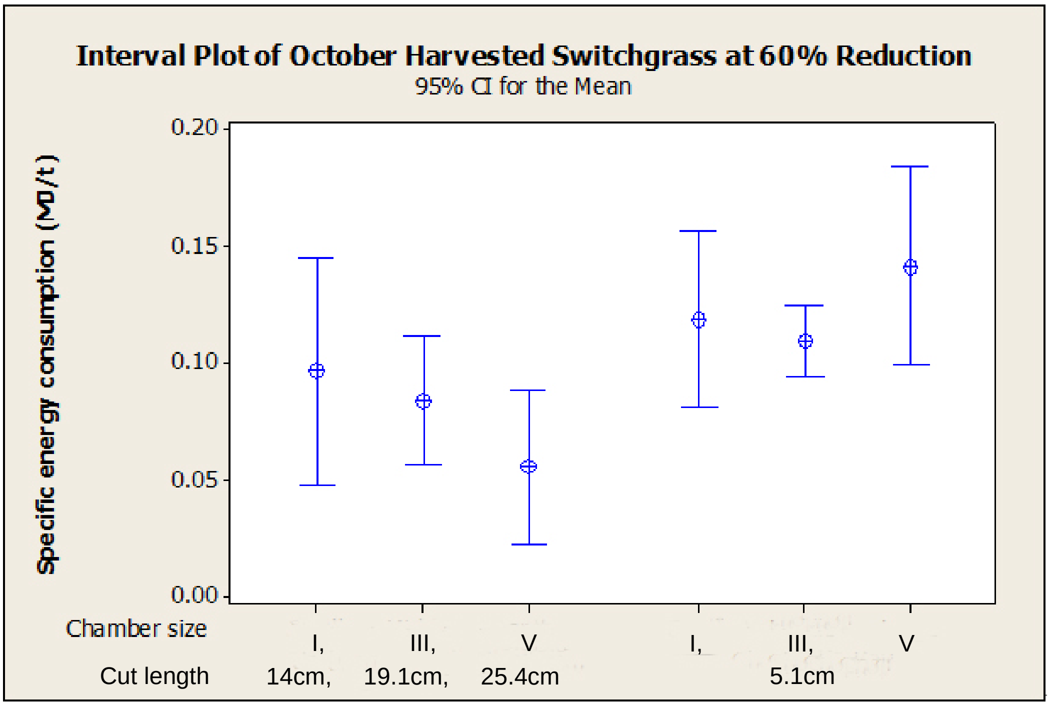


Figure 8. 2. Specific energy consumption interval plot of Switchgrass at 60% Volume reduction.

Table 8. 3. Specific energy consumption of Switchgrass at 60% Volume reduction.

Crops	Harvest time	Chamber size	Particle size(cm)	Arrangement	Specific energy consumption(MJ/t)		Std.Dev.
Switchgrass	Oct.2013	Small	14.0	parallel	0.0965	ab	0.0197
	Oct.2013	Middle	19.1	parallel	0.0841	ab	0.0023
	Oct.2013	Large	25.4	parallel	0.0556	a	0.0028
	Oct.2013	Small	5.1	random	0.1188	bc	0.0288
	Oct.2013	Middle	5.1	random	0.1092	abc	0.0062
	Oct.2013	Large	5.1	random	0.1414	c	0.0021

Note: Means with the same letter are not significantly different from each other (Tukey HSD[a] test), and the mean difference is significant at the 0.05 level.

For corn stover, the average moisture contents harvested in October and December were 19.62±4.02% (w.b.), and 21.02±2.81% (w.b.), respectively. No evidence found that the specific energy consumption of October harvested corn stover was different than the corn stover collected in December (Figure 8). However, the large chamber size had the smallest specific energy consumption value than the other two sizes. There were no significant differences between Oct. and Dec. collected corn stover in the large compression chamber (Table 4).

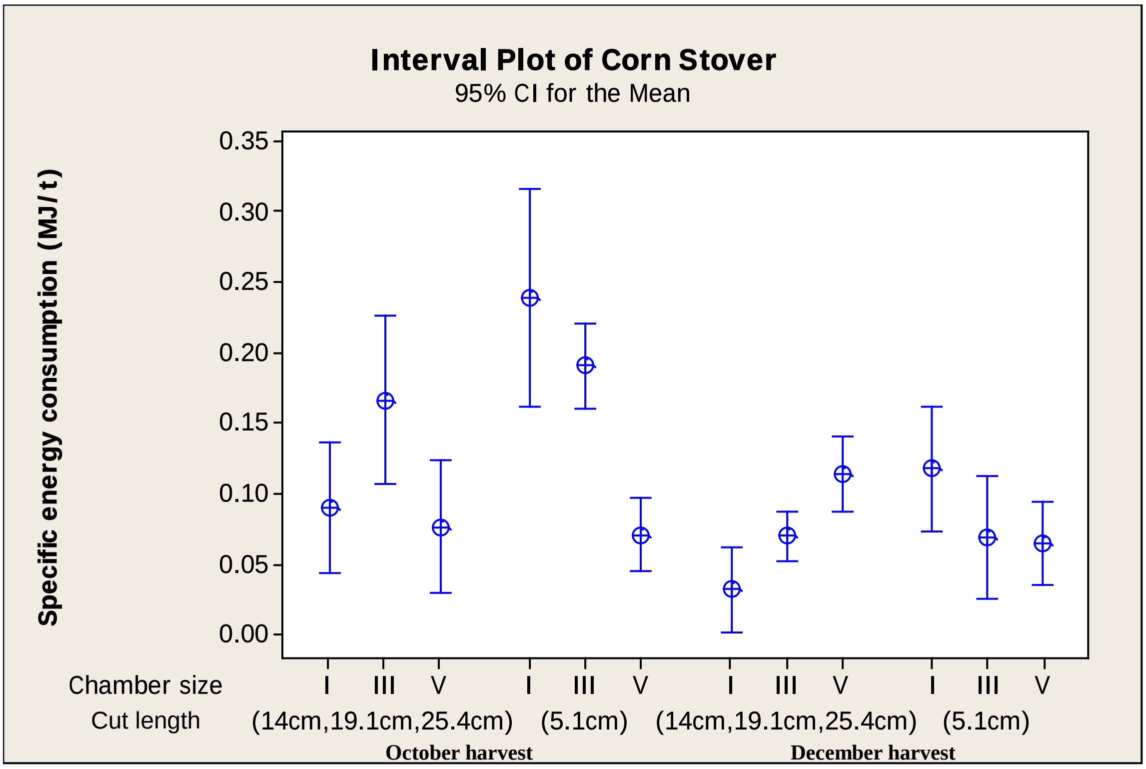


Figure 8. 3. Specific energy consumption interval plot of Corn stover at 60% Volume reduction.

Table 8. 4. Specific energy consumption of Corn stover at 60% Volume reduction.

Crops	Harvest time	Chamber size	Particle size(cm)	Arrangement	Specific energy consumption(MJ/t)		Std.Dev.
Corn stover	Oct.2013	Small	14.0	parallel	0.0901	ab	0.0343
	Oct.2013	Middle	19.1	parallel	0.1666	cde	0.0066
	Oct.2013	Large	25.4	parallel	0.0764	ab	0.0141
	Oct.2013	Small	5.1	random	0.2395	e	0.0128
	Oct.2013	Middle	5.1	random	0.1907	de	0.0062
	Oct.2013	Large	5.1	random	0.0707	ab	0.0050
	Dec. 2013	Small	14.0	parallel	0.0316	a	0.0325
	Dec. 2013	Middle	19.1	parallel	0.0698	ab	0.0067
	Dec.2013	Large	25.4	parallel	0.1136	bc	0.0027
	Dec. 2013	Small	5.1	random	0.1174	bcd	0.0217
	Dec. 2013	Middle	5.1	random	0.0692	ab	0.0126
	Dec. 2013	Large	5.1	random	0.0641	ab	0.0050

Note: Means with the same letter are not significantly different from each other (Tukey HSD[a] test), and the mean difference is significant at the 0.05 level.

Chapter 9 – Conclusions and Recommendations

Larger compression chamber had significant lower specific energy consumption in bulk compression process. This indicated that he larger the chamber was the more efficient it would be when compressing these crops. For switchgrass and corn stover, chamber size had no significant influence on energy consumption when the volume reduction was less than 70%. For miscanthus, 60% or lower volume reduction showed no significant influence from chamber size.

The parallel arrangement method may decrease the compression energy consumption. In real production, making stems in the same direction parallel before baling the grass could be a good choice. Especially for miscanthus which has higher initial bulk density when the stems were arranged parallel in the compression chamber. In most cases, the chopped biomass with shorter particle sizes had higher specific energy consumption than longer particle sizes, but not significant. For corn stover particle size had less influence on compression energy compared to switchgrass and Miscanthus due to its relatively complicated composition and loose condition.

Switchgrass harvested in fall and spring seasons had no signification differences in compression energy consumption when the moisture contents were similar. However, there was significant difference in specific energy consumption between corn stover collected in Oct. and Dec. Additional two months standing in snow significantly decrease 44%-11% compression specific energy consumption. The lower the volume reduction it achieved, the more energy consumption it saved.

During the compression progress, the specific energy consumption increased sharply after a specific point. In the range of 60% to 88% volume reduction, the 60% volume reduction had the lowest specific energy consumption. Energy consumption at 70% volume reduction could double the energy consumption compared to that of 60% volume reduction. The specific energy consumption became as 5 times high as that at 60% volume reduction was increased to 80%. To reach 88% volume reduction, the specific energy was consumed as 20 times as 60%'s.

In this study, the value of the suggested volume reduction is 44%-72% due to the different chamber size. The larger chamber size would be easier to reach a level of volume reduction with less energy consumption. As the result, 60%-70% volume reduction should be a good choice for bale bulk densification.

References:

Adapa, P., and L. Tabil. 2009. Compaction characteristics of barley, canola, oat and wheat straw. Biosystems Engineering. 104: 335-344.

Adapa, P. K., G. J. Schoenau, L. G. Tabil, E. A. Arinze, A. Singh A, and A. K. Dalai. 2007. Customized and value-added high quality alfalfa products – a new concept. Agricultural Engineering International. 6: 1–28.

ASAE Standards 47th ed. 2003, S358.2- Moisture measurement-forages. American Society of Agricultural Engineers, St Joseph, MI. pp. 595.

Bechen, K. 2011. Biomass 2012: International Growth and Domestic Obstacles. Available at http://biomassmagazine.com/articles/5988/biomass-2012-international-growth-and-domestic-obstacles. Accessed 16 October 2012.

Bellinger, P. L., and H. H. McColly. 1961. Energy requirements for forming hay pellets. Agricultural Engineering. 42(5): 244–247.

Bhattacharya, SC., GY. Saunier, N. Shah, and N. Islam. 1985. Densification of biomass residues in Asia. Elsevier Applied Science Publishers. 84 (3): 559-563.

Campbell, C. A., R. P. Zentner, S. Gameda, B. Blomert, and D. Wall. 2002. Production of annual crops on the Canadian prairies: trends during 1976–1998. Canadian Journal of Soil Science. 82: 45–57.

Caparella, T. 2012. U.S. Renewable Fuel Standards Finalized for 2012. Available at http://rendermagazine.com/articles/2012-issues/february-2012/us-renewable-fuel-standards-final ized-for-2012/. Accessed 10 December 2012.

Environmental Protection Agency (EPA). 2012. Supplemental Determination for Renewable Fuels Produced Under the Final RFS2 Program From Grain Sorghum. Available at http://www.epa.gov/otaq/fuels/renewablefuels/documents/sorghum-final-rule.pdf. Accessed 30 September 2012.

Faborode, M.O., and J. R. O'Callaghan. 1987. Optimizing the compression/briquetting of fibrous agricultural materials. Journal of Agricultural Engineering Research. 38: 245–262.

FPL. 2004. Fuel Value Calculator. Forest Products Laboratory. Available at http://www.fpl.fs.fed.us/documnts/techline/fuel-value-calculator.pdf. Accessed 30 September 2012.

Gustafsson, O., and M. Krusa. 2009. Brown Clouds over South Asia: Biomass or Fossil Fuel Combustion. Science 323 (5913): 495–8.

Grover, P. D., and S. K. Mishra. 1996. Biomass briquetting: technology and practices. Bangkok, Thailand: Regional Wood Energy Development Program in Asia.

Holley, C.A. 1983.The densification of biomass by roll briquetting. Proc Institute for Briquetting and Agglomeration (IBA). 18:95-102.

Kaliyan, N., and R. V. Morey. 2006a. Factors affecting strength and durability of densified products. ASABE Paper No. 066077. St. Joseph, MI: ASABE.

Kaliyan, N., and R. V. Morey. 2006b. Densification characteristics of corn stover and switchgrass. ASABE Paper No. 066174. St. Joseph, MI: ASABE.

Kaliyan, N., and R. V. Morey. 2007. Roll press briquetting of corn stover and switchgrass: a pilot scale continuous briquetting study. ASABE Paper No. 076044. St. Joseph, MI: ASABE.

Kemmerer, B. D. and J. Liu. 2011. Comparison of large square bale handling options. ASABE Paper No. 1111265. St. Joseph, MI: ASABE.

Li, Y., and H. Liu. 2000. High-pressure densification of wood residues to form an upgraded fuel. Biomass and Bioenergy. 19:177–186.

Liu, R., H. Yu, and Y. Huang. 2005. Structure and morphology of cellulose in wheat straw. Cellulose. 12: 25–34.

Liu, J., and R. Grisso. 2012. Harvest systems and analysis for herbaceous biomass. Chapter 5, In: Biomass.

Mani, S., L. G. Tabil , and S. Sokhansanj. 2002. Compaction Behavior of Some Biomass Grinds. AIC 2002 Meeting, CSAE/SCGR Program, Saskatoon, Saskatchewan. AIC Paper No. 02-305.

Mani, S., L. G. Tabil, and S. Sokhansanj. 2003. An overview of compaction of biomass grinds. Powder Handling & Process, 15(3): 160–168.

Mani, S., L. G. Tabil, and S. Sokhansanj. 2006. Specific energy requirement for compacting corn stover. Bioresource Technology. 30: 648–654.

McLaughlin, B., and A. Kzos. 2005. Development of switchgrass (Panicum virgatum) as a bioenergy feedstock in the United States. Biomass and Bioenergy. 28: 515-535.

McMullen, J., O. O. Fasina, C. W. Wood, and Y. Feng. 2005. Storage and handling characteristics of pellets from poultry litter. Applied Eng in Agric. 21:645-651.

Mewes, E. 1959. Verdichtungsgesetzmassigkeiten nach presstopfversuchen (Compression relationships as a result of experiments in pressure chambers). Landtechnische Forschung, 9(3):

68–76.

Obernberger, I., and G. Thek. 2004. Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behavior. Biomass and Bioenergy. 27:653-669.

O'Dogherty, M. J., and J. A. Wheeler. 1984. Compression of straw to high densities in closed cylindrical dies. Journal of Agricultural Engineering Research, 29: 61–72.

O'Dogherty, M. J. 1989. A review of the mechanical behavior of straw when compressed to high densities. Journal of Agricultural Engineering Research, 44: 241–265.

Pietsch, W. 2002. Agglomeration processes– phenomena, technologies, equipment. Weinheim, German: Wiley-VCH.

Sokhansanj, S., and H.C. Wood. 1991. Engineering aspects of forage processing for pellets, cubes, dense chops and bales. Advances in Feed Tech. 5: 6-23.

Sokhansanj, S., and A. F. Turhollow. 2004. Biomass densification – cubing operations and costs for corn stover. Applied Engineering in Agriculture. 20(4): 495−499

Sokhansanj, S., S. Mani, X. Bi, P. Zaini, and L. G. Tabil, 2005. Binderless pelletization of biomass. ASABE Paper No. 056061. St. Joseph, Mi: ASABE.

Sokhansanj, S., S. Mani, M. Stumborg, R. Samson and J. Fenton. 2006. Production and distribution of cereal straw on the Canadian prairies. Canadian Biosystems Engineering. 48: 3.39–3.46.

Stevens, C.A. 1987. Starch gelatinization and the influence of particle size, steam pressure and die speed on the pelleting process. PhD Dissertation. Kansas State University, Manhattan, KS.

TSEC. 2001. Plant Crops Bioenergy Research UK. TSEC-Biosys. Available at http://www.tsec-biosys.ac.uk/index.php?p=8&t=1&ss=5. Accessed 30 September 2012.

Varadharaju, N., and L. Gothandapani. 1998. Design and development of equipment for pelleting decomposed coir pith. Agric Mech in Asia, Africa and Latin America. 29(2): 33,34,38.

Wang, T., G. Wang, D. Wang, and L. G. Tabil. 2012. Investigation of the Compression Characteristics of Leymus chinensis L. ASABE Paper No. 1341112. St. Joseph, Mi: ASABE.

Zhang, J., and Smith, K. R. (2007). "Household Air Pollution from Coal and Biomass Fuels in China: Measurements, Health Impacts, and Interventions". Environmental Health Perspectives 115 (6): 848–855.