An ASABE Meeting Presentation

Paper Number: 076058

Physical characterization of wet and dry wheat straw and switchgrass – bulk and specific density

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Written for presentation at the
2007 ASABE Annual International Meeting
Sponsored by ASABE
Minneapolis Convention Center
Minneapolis, Minnesota
17 - 20 June 2007

Abstract. *Bulk density of biomass is a major factor in determining the cost and logistics requirements of handling and moving biomass from farm to biorefinery. Bulk density is a strong function of size and shape and individual particle density. In this research we study experimentally the effect of particle length, moisture content, and particle density on bulk density of wheat straw and switchgrass. Wheat straw and switchgrass stems were cut to exact nominal lengths of 6, 12, 25, and 50 mm. The moisture contents of biomass samples were adjusted upward from an original 8% to 20, 40, and 60%. Three particle densities were measured assuming two structural geometries for the stems; i.e a hollow cylinder and a solid cylinder. The particle densities were measured using a gas pycnometer at a gas* *pressure of 40 kPa. The bulk density of both loose-fill and packed-fill were examined. The bulk density of wet straw and switchgrass increased with moisture content from 24.16 to 111.13 kg/m^3 for straw and from 49.44 to 266.52 kg/m^3 for switchgrass. The corresponding tapped bulk density was 33.75 to 130.43 kg/m^3 for straw and 67.68 – 323.10 kg/m^3 for switchgrass. The increase in bulk density due to tapping the container was from 10% for short 6 mm particles to more than 50% for long 50 mm particles. It is concluded that the following mixture equation can be used for estimating bulk density of the same size material from particle moisture content* $\frac{1}{\rho_b} = \frac{1 - M_w}{ax^{-b}} + \frac{M_w}{\rho_w}$ *where* ρ_b *is the wet bulk density of biomass at a moisture content of* M_w *(decimal fraction wet basis), x is particle length, a and b are biomass species constants, and* ρ_w *is the density of water (roughly 1000 kgm^{-3}).*

Keywords. bulk density, particle density, straw, switchgrass, packing, porosity, fibrous biomass

INTRODUCTION AND OBJECTIVES

Agricultural crop residues and perennial energy crops account for about 80% of the total biomass feedstock from agricultural lands available to produce fuels, chemicals and materials (Perlack et al., 2005). Efficient and economic conversion of biomass into various products in a biorefinery relies on consistent and economic transport of biomass from the field to a biorefinery. One of the major factors affecting the delivery cost of biomass is its bulk density during collection and transport (Sokhansanj et al. 2006). Bulk density of biomass is a key parameter that not only decides the cost of feedstock delivered to a biorefinery, but also affects the design and operation of conveyors, storage silos and processing and heat transfer equipment (Woodcock and Mason 1987). Bulk density of biomass (ρ_b) depends on material composition (c), particle shape (ϕ) and size (*l, d*), orientation of particles (*s*), specific density of individual particles (ρ_p), particle size distribution (PSD), moisture content (*w*), and applied axial pressure (*P*) (Peleg, 1983).

$$\rho_b = f(c, \rho_p, l, d, \phi, s, PSD, w, p) \qquad (1)$$

where *l* and *d* are length and diameter of particles. Not all variables in the right hand side of equation 1 are independent of each other. For example moisture content has an effect on particle density and packing. Similarly, particle size and distribution depends on the type of pre-processing methods used during the preparation of the material such as chopping, drying, grinding, sieving etc. Length (*l*) and diameter (*d*) define a shape factor (ϕ) for the particle. Other factors such as surface characteristics affect the bulk density as well.

Previous work on measurement of bulk density of fibrous materials showed that the larger particles have low bulk density, as they occupy more pore volume than smaller particles (Mani et al., 2004). Within the range of biomass particle sizes from 1.4 mm to 0.18 mm studied, particle size was inversely proportional to the bulk density of the material. In practice, the size of the biomass particles transported from the field ranges from a foot to an inch long. Our previous work on the interaction of particle size, moisture content on bulk density of wood chips showed that no significant effect on particle size of wood chip on bulk density, but showed significant effect on the moisture content on the bulk density of wood chips within the moisture content range of 55-10% (wet basis) (Hoque et al., 2006). However, the effect of particle size and moisture content on bulk density of straws and energy crops is not clear from the previously reported studies.

The agricultural crop biomass particles are usually cylindrical or disk shape depending upon the part of the plant they originate. The long length particles with aspect ratio of l/d>1 are classified as cylindrical while the short particles (l/d<1) are classified as disk. The packing behavior of these non-spherical shapes usually start from studying the mono-sized particles (Zou et al., 1996; Zhang et al., 2006) and then gradually move to the particle mixtures with different shapes and volume fractions (Yu et al., 1996; Zou et al., 1997).

Previous research has evaluated the packing of mono-sized non-spherical particles (cylinders and disks) and general equations for the estimation of the initial porosity (defined as the porosity of mono-sized particles) from sphericity of the particles have been formulated for the loose and dense packings (Zou et al., 1996). A modified linear packing model for predicting the porosity of non-spherical particle mixtures was further developed (Yu et al., 1996). Later, it was found the cylindrical particles exhibit different particle packing behavior than the spherical shape particles. Long cylindrical particles are heavily dependent on the length distribution of particles (Zou et al., 1997). They cannot be predicted by analogy to that for spherical particles packing. The shape and size effect contribute to the packing structure of the non-spherical particles and the shape effect dominates the packing structure with a wider length distribution. But almost all of the literature indicated that the test materials were mostly solid cylindrical particles with equilateral dimensions. Straws and switchgrass are hollow-tube structures with non-uniform diameter along the particle length.

The objective of this research is to measure the bulk density of biomass with respect to some of the measurable physical attributes and develop predictive equations for bulk density of biomass. The significance of this work is to study the effect of moisture content and particles size (with an exact length) on the bulk density of the straws and switchgrass. The optimized physical properties of the energy crop and agricultural residues can help to maximize amount of material per load within legal restrictions and provide useful packing information for chemical processes.

MATERIALS AND METHODS

Sample preparation

The wheat straw was collected from Richmond Country Farms, Richmond, BC. The bales were of rectangular shape with a moisture content of 8.45 % wet basis (wb) as received. The switchgrass was a round bale brought in from a farm in Manitoba. The moisture content of switchgrass was 7.96 % wet basis (wb) as received. The moisture contents were measured using ASAE Standard S358.2 FEB 03 (ASAE 2005) for forages, drying 5-20 g sample in a convection oven at 105 ^{o}C for 24 h.

The stems of straw and switchgrass were sorted out manually. The leafy material and small pieces were removed. The stems were cut into various nominal sizes of 50.80 mm (2”), 25.40 mm (1”), 12.70 mm (1/2”) and 6.35 mm (1/4”) using a scissor. The actual particles size of switchgrass and straw are listed in Table 1.

The moisture content of switchgrass and straw was adjusted by spraying a predetermined amount of distilled water uniformly over the samples in a container. The moistened samples were thoroughly mixed and sealed inside a plastic bag. The bags were placed inside a sealed plastic container for 48 h at 4^{o}C to allow the samples to equilibrate to three levels of target moisture content (i.e., 20%, 40% and 60% wb). The final moisture contents were measured using air oven method (ASAE 2005).

Bulk density

Bulk density measurement of wheat straw and switchgrass was determined according to the ASAE Standard S269.4 DEC 01 (ASAE 2005). Three cylindrical containers each with a specific inside diameter (D_T) were used for determination of bulk density of different particle sizes (Table 1). Each measurement was repeated 5 times using the same straw or switchgrass sample. Biomass was poured into the container from a certain height until the container was overflowed. The height of pouring for 50 mm and 25 mm long particles was 500 mm and for 12.5 and 6 mm long particles was 200 mm. The height of pour was measured from the bottom of the container. The excess material was removed by striking a straight edge across the top. The weight of the material with the container was recorded. The net weight of the sample was obtained by subtracting the weight of the empty container. For tapped density, the loosely filled container was tapped on the laboratory bench 5 times. Filling and tapping was repeated until the container was overflowed. The filled container was weighed to 0.01g precision. Bulk density was calculated by dividing the mass over the container volume.

Particle density

The straw and switchgrass are hollow cylindrical particles for particle density calculation (ρ_p) as shown in Figure 1. The solid cylindrical structure was also used for particle density calculation for comparison. The samples were oven dried at 105oC for 24 hours before any physical dimensions measurement. Ten samples (n = 10) for each different length and each species were randomly picked up for the length and weight measurement. The length (l), diameter (D_{out}) and the thickness (t) of the particles were measured using a 150 mm Mastercraft digital caliper with a precision of 0.01 mm. The average diameter of the samples was taken as the average value of the diameter in both ends and the middle of the samples along the length of the sample. The thickness of the sample assumed to be uniform for the particle density measurement. The weights (m_p) of the particles were measured using A&D GR200 digital balance with a precision of 0.1 mg.

The particle density measurement of each sample was determined from the following equations:

$$\rho_p = \frac{m_p}{V_{p,hollow}} \tag{2}$$

$$t = \frac{D_{out} - D_{in}}{2} \tag{3}$$

$$V_{p,hollow} = \left(2rt + t^2\right)\pi l \tag{4}$$

$$V_{p,solid} = \pi r^2 l \tag{5}$$

where ρ_p is the particle density of the samples after drying (kg/m^3), m_p is the mass of the samples (kg), t is the thickness of the inner wall of the samples, D_{in} is the inner diameter of the samples (m), D_{out} is the outer diameter of the samples (m), $V_{p,\ hollow}$ is the actual volume of the hollow cylindrical samples (m^3) and $V_{p,\ solid}$ is the actual volume of the solid cylindrical samples (m^3).

Solid density

The solid particle density of the samples was measured using a gas multipycnometer (Quantachrome Corporation, FL). The instrument measures the volume of the particle from the pressure difference between a known reference volume (V_R) and the volume of sample cell (V_c). Nitrogen is used as the gas to fill the reference and sample cells. The pressure is set at around 40 kPa. The pycnometer volume of the sample (V_p) is calculated from Equation 6.

$$V_p = V_c - V_R\left(\frac{P_1}{P_2} - 1\right) \tag{6}$$

where P_1 is the pressure reading after pressurizing the reference volume (kPa), P_2 is the pressure after including the volume of the cell (kPa). The pycnometer particle density (ρ_s) of the sample is its mass m_p divided by the pycnometer particle volume (V_{pvc}) by equation 7

$$\rho_s = \frac{m_p}{V_{pvc}} \tag{7}$$

The measurement of solid density for wheat straw and switchgrass with different sizes was repeated three times (n = 3).

Hausner ratio

Hausner ratio (Hr) is used to quantify the inter particle friction. The ratio is defined as the ratio of tapped density to the loose bulk packing density,

$$Hr = \frac{\rho_{b,wet\_tapped}}{\rho_{b,wet\_loose}} \tag{8}$$

where ρ_{b,wet_tapped} is the tapped bulk density (wb) of the samples (kg/m^3) and ρ_{b,wet_loose} is the loose bulk density (wb) of the samples (kg/m^3)

Sphericity

Sphericity (φ) is a shape factor that describes the proximity of the shape of the particles to a perfect sphere. It is defined as the ratio of the surface area of a sphere of the same volume as the particle divided by the actual surface area (A_p) of the particle (McCabe, 2004). For the straws and switchgrass (assumed as hollow cylindrical particles) the following equations were used for sphericity calculation.

$$V_{p,hollow} = \pi\left(\frac{D_{out}}{2}\right)^2 l \tag{9}$$

$$A_p = 2\pi\left[\left(\frac{D_{out}}{2}\right)l + \left(\frac{D_{out}}{2}\right)^2\right] \tag{10}$$

$$\phi = \frac{\pi^{\frac{1}{3}}\left(6V_{p,hollow}\right)^{\frac{2}{3}}}{A_p} \tag{11}$$

where $V_{P,hollow}$ is the hollow particle volume (m^3), l is the particle length (m), D_{out} is the diameter of the particle (m) and A_p is the actual surface area of the particle (m^2)

Wet and dry bulk density

The relationship of the wet based (w) and dry (d) bulk density of the samples is represented as a mixture equation in two forms of Eq. (12) (Peleg, 1983) or Eq. (13) (Hollenbach et al, 1982)

$$\frac{1}{\rho_b} = \frac{1-M_w}{\rho_d} + \frac{1}{\rho_w} \tag{12}$$

$$\rho_b = \rho_d\left(1+M_w\right) \tag{13}$$

where ρ_b is the wet based bulk density of the samples (kg/m^3) at moisture content of Mw, ρ_d is the dry based bulk density (kg/m^3) at bone dry sample. M_w is the moisture content of the wet samples (decimal wet basis), ρ_w is the bulk density of water 1000 kg/m^3.

Porosity

The porosity of dry bulk was calculated as equation 14:

$$\varepsilon_o = 1 - \frac{\rho_d}{\rho_p} \tag{14}$$

where ε_o is the dry based bulk porosity, ρ_d is the bulk density (dry) and ρ_p is the particle or solid density (dry) of the samples.

RESULTS

Wet bulk density measurement

Table 1 lists the length of particles and diameter of the container in which the bulk volume of straw and switchgrass were measured. The ratio of the container diameter to the length of particles ranged from 5.38 to 24.00. Zou et al. (1996) states that the diameter of the column should be at least 20 times the equivalent volume diameter of cylindrical particle in order to minimize the edge effect on the amount of equilateral cylinders that can be packed into the container. Therefore the mass variations for packing larger particles in the container were larger. This needs to be further investigated in order to design containers that would give consistent bulk density values.

Figure 2 shows the loose bulk density of switchgrass varies from 49.44 to 266.52 kg/m^3 in the moisture content range of 8 to 60 % for four different particle sizes. Similar trend was also observed for the wheat straw in which the loose bulk densities ranged from 24.16 to 111.13 kg/m^3 in the same moisture content range for four different particle sizes. The bulk density of the same size particles of straw was roughly half of that of the bulk density of switchgrass particles at the same moisture content. Bulk density increased with moisture content of particles. The effect of moisture content on bulk density will be discussed

The tapped bulk densities (wb) of wheat straws and switchgrass vary from 33.75 to 323.1 kg/m^3 and from 67.68 to 323.1 kg/m^3, respectively for the moisture content range of 8 to 60 % for four different particle sizes. Figure 3 shows the percent increase in bulk density from loose to tapped material. The percent increase is the highest for longer biomass particles than for shorter particles. For most tests tapping switchgrass produced a larger percentage increase in bulk density than wheat straw. Visually we could not detect the influence of moisture content on bulk density change due to tapping.

The relationship between the bulk density and particle size can best described by power law equations in the form of

$$\rho_b = ax^{-b} \tag{15}$$

where y is the bulk density and x is the nominal particle size. Table 4 lists constants *a* and *b* and R^2 for Eq. (15). Generally, the bulk density of the straw and switchgrass increased with moisture content while decreased with increasing particle length.

Single particle physical dimensions and specific density

Table 2 lists particle dimension, volume, and density for switchgrass and straw. The diameter of switchgrass (2.42 - 2.92 mm) was similar to those of wheat straws (2.65 - 3.38 mm) for all different particle lengths. However, the thickness of the switchgrass (0.34 - 0.581 mm) was two to four times thicker than that of wheat straw (0.125 – 0.216 mm) at the same nominal particle length. In addition, the mass of a single piece of switchgrass nearly doubles that of the wheat straws at the same nominal particle length. This agrees with the wet based bulk density of switchgrass that we determined to be twice as that of wheat straws as shown in Figure 2. The mass of each single particle is proportional to the wet based bulk density.

The specific density measured by the multipycnometer were 0.93 – 1.18 for the wheat straw and 0.62 - 0.65 for switchgrass. These values are much higher than the particle densities value calculated from their mass and the volume assuming the hollow and solid cylindrical shape for the particles (Table 3). The difference in density is due to the exclusion of pore volumes measured by pycnometer.

Relationship between wet and dry bulk density

Equations 12 and 13 for predicting the wet based bulk density from the dry bulk density were compared. We assumed the measured bulk density at 8% moisture content to be the dry bulk density. We then calculated bulk density of switchgrass and straw at 20, 40, and 60% moisture content using Eqs. 12 and 13. Figure 4 shows sum of errors between the predicted and measure values and the sum of squares are 1187 for wheat straws and 2751 for switchgrass respectively for loose bulk density. Eq. 13 predicted a larger bulk density than the measured values for both wheat straw and switchgrass. Combining Eqs. 12 and 15, Eq. 16 is developed to predict the wet bulk density from the initial dry based bulk density of wheat straw and switchgrass at different particle lengths and at different moisture contents.

$$\frac{1}{\rho_b} = \frac{1 - M_w}{ax^{-b}} + \frac{M_w}{\rho_w} \tag{16}$$

where ρ_b is the wet bulk density of biomass at a moisture content of M_w (decimal fraction wet basis), x is the particle length (mm), a and b are the constants obtained from the Table 4 of corresponding species at 8% moisture content for corresponding tapping mode and ρ_w is the density of water (roughly 1000 kgm^{-3}). For example, the constants for predicting the loose packing of wheat straw bulk densities (wb) are 113.79 for **a** and 0.389 for **b**.

Dry based bulk voidage/porosity

Dry based bulk voidage/porosity is calculated to determine the actual packing of the materials on a dry basis. Figure 5 shows the effect of the moisture content and sphericity of the particles on the dry based bulk porosity of switchgrass during loose packing assuming the particles with solid and hollow cylindrical shapes respectively. The dry based bulk porosity of switchgrass and wheat straw decreased from 0.96 to 0.54 and from 0.98 to 0.89 respectively with increasing sphericity for the loose packing considering hollow particles. When the particles length is long (i.e., the sphericity is small), its length restricts the particles to move with respect to each other for a closer packing for the cylindrical particles and this is in agreement with the previous study that the packing of cylindrical particles heavily dependent upon particle length distributions (Zou et al., 1997).

Zou et al. (1996) related porosity to sphericity of the solid equilateral cylindrical particles by the previous work. The initial porosity and the sphericity relationship are described for loose packing,

$$\ln \varepsilon_{ol,cylinder} = \varphi^{5.58} \exp[5.89(1-\varphi)] \ln 0.4 \tag{17}$$

And for dense packing.

$$\ln \varepsilon_{od,cylinder} = \varphi^{6.74} \exp[8.00(1-\varphi)] \ln 0.36 \tag{18}$$

Figure 5 shows that the measured porosity of the switchgrass is much higher than the predicted value from the model for both loose and dense packing. This may be explained by the hollow cylindrical structures of biomass and the internal hollow voids act as additional porosities (Dixon, 1988). The porosity measured assuming the solid cylinders obviously is lower than the hollow one, however it is still a bit higher than the values predicted by the model due to the non-equilateral size. These form less contact points to each of the surface of the materials as compared to the solid equilateral cylindrical particles.

Tapping allowed the fibers to rearrange to a horizontal position and repack with a denser packing and hence leading to a higher packing density. It was observed that the particles fill up the voids near the wall of the container under tapping. This observation agrees with a previous research that cylindrical particles packed loose inside a vertical cylindrical container ($D_T/L = 2.71$, $\varepsilon \sim 0.5$) were transformed into a highly ordered packing ($\varepsilon \sim 0.25$) with vertical orientation near the wall under vibration (Villarruel et al., 2000). Zhang et al. (2006) reported the near wall porosity is higher than the interior porosity for equilateral cylindrical particles described by the radial distribution function (Zhang et al., 2006). The high porosity near the wall was attributed to the contact of the single corner point of the cylinder instead of the parallel or orthogonal contact to the wall. Therefore, tapping motion is suggested to be useful in packing the cylindrical particles into a higher density state.

Hausner ratio

Hausner ratio is used to quantify the interparticle friction which restricts the close packing of the particles. Zou et al. (1996) presented a general correlation between Hausner ratio and sphericity of the particles represented by equation 19,

$$Hr = 1.478 \times 10^{-0.136\phi} \tag{19}$$

Figure 6 shows the Hausner ratio of the packing of switchgrass at different sphericity. The trend is in agreement with the model. The Hausner ratio decreases with the increase of sphericity. When the particle length is small (i.e. the sphericity is high), the Hausner ratio of the samples are closed to the value predicted by the model. All of the measured Hausner ratios for different sphericity of the particles are greater than the predicted values from the model; especially the deviation of the calculated Hausner ratio of the samples is large from the model when the sphericity of the particles is small. Higher moisture contant particles also have a higher hausner ratio than the Zou et al.'s Eq. 19.

CONCLUSIONS

The following conclusions are drawn from this work.

- The bulk density of Switchgrass ranged from 50 to 265 kg m^{-3} for loose fill and from 68 to 325 kg m^{-3} for packed fill after tapping. For straw these values ranged from 24 to 111 kgm^{-3} for loose fill and from 46 to 130 kgm^{-3} for the packed fill.
- Longer particles resulted in a larger percentage increase in packing than the smaller particles by tapping. In some cases the increase in bulk density as a result of packing was more than 50%. Increase in bulk density of small particles (6 mm) was about 10%.
- For estimating bulk density of a moist material from the bulk density of dry material we found less bias and deviation from actual measured values when using $\frac{1}{\rho_b} = \frac{1-M_w}{ax^{-b}} + \frac{M_w}{\rho_w}$ where ρ_b is the wet bulk density of biomass at a moisture content of M_w (decimal fraction wet basis), x is the particle length (mm), a and b are the constants and ρ_w is the density of water (roughly 1000 kgm^{-3}).
- Hausner ratio is a ratio of tapped bulk density over the loose bulk density and it did not fit well to the data of this study.
- Individual particle density is dependent upon the way we calculate or measure the volume of the particles. Assuming that a particle is a solid cylinder, the bulk density of wheat straw was about 90 kgm^{-3}, assuming it was a hollow cylinder the bulk density was 500 kgm^{-3}, and measuring the volume using a pycnometer, the particle density was roughly 1100 kgm^{-3}. The corresponding values for switchgrass were 230 for solid, 400 for hollow and 650 kgm^{-3} for pycnometer measurements.
- Further work is required to determine an optimum size for the container for bulk density measurement and a procedure for loose and pack fills. We also need to measure the volume change of a given quantity of biomass as the moisture content is decreased. This work should be repeated with freshly harvest material of high moisture content. We also want to compare the result of this work which is on exact length to the results when biomass has a size distribution.

Acknowledgements

This research is made possible through a USDA/DOE Grant to the University of Tennessee and a sub contract to the University of British Columbia. The financial assistance from the Oak Ridge National Laboratory in support of the logistics project is acknowledged. NSERC's Discovery and Strategic Grants supported the work of graduate students on this and related projects.

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List of nomenclature

A_p,	Actual surface area of the particle (m^2)
a, b	Biomass species constants
D_{in}	Inner diameter of the samples (mm)
D_{out}	Outer diameter of the samples (mm)
D_T	Diameter of the container for bulk density measurement (mm)
H	Height of the container for bulk density measurement (mm)
Hr	Hausner ratio that is used to quantify the inter particle friction.
l	Particle length (mm)
M_w	Moisture content of the wet samples (decimal wet basis)
m_p	Mass of the samples (g)
P_1	Pressure reading after pressurizing the reference volume (kPa)
P_2	Pressure after including the volume of the cell (kPa)
t	Thickness of the inner wall of the samples (mm)
$V_{p,\ hollow}$	Actual volume of the hollow cylindrical samples (m^3)
$V_{p,\ solid}$	Actual volume of the solid cylindrical samples (m^3)
V_{pvc}	Pycnometer particle volume (m^3)
ε_o	Dry based bulk porosity
ρ_b	Wet based bulk density of the samples (kg/m^3) at moisture content of M_w
ρ_{b,wet_tapped}	Tapped bulk density (wb) of the samples (kg/m^3)
ρ_{b,wet_loose}	Loose bulk density (wb) of the samples (kg/m^3)
ρ_d	Dry based bulk density (kg/m^3) at bone dry sample.

ρ_p	Particle density of the samples after drying (kg/m^3)
ρ_s	Particle density measured by pycnometer (kg/m^3)
ρ_w	Bulk density of water (1000 kg/m^3)
φ	Sphericity which is a shape factor that describes the proximity of the shape of the particles to a perfect sphere.

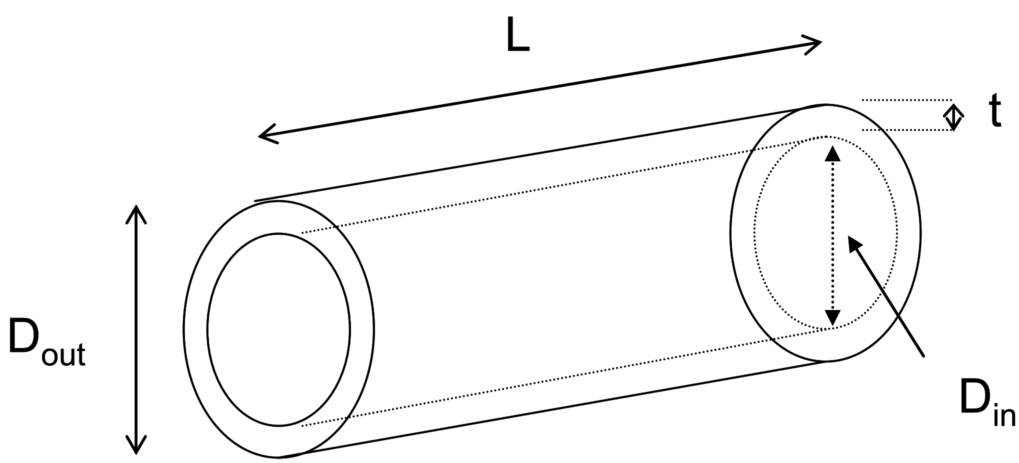

Figure 1: Physical dimensions of a stem assuming cylindrical shape (L: length, D: diameter, T: wall thickness)

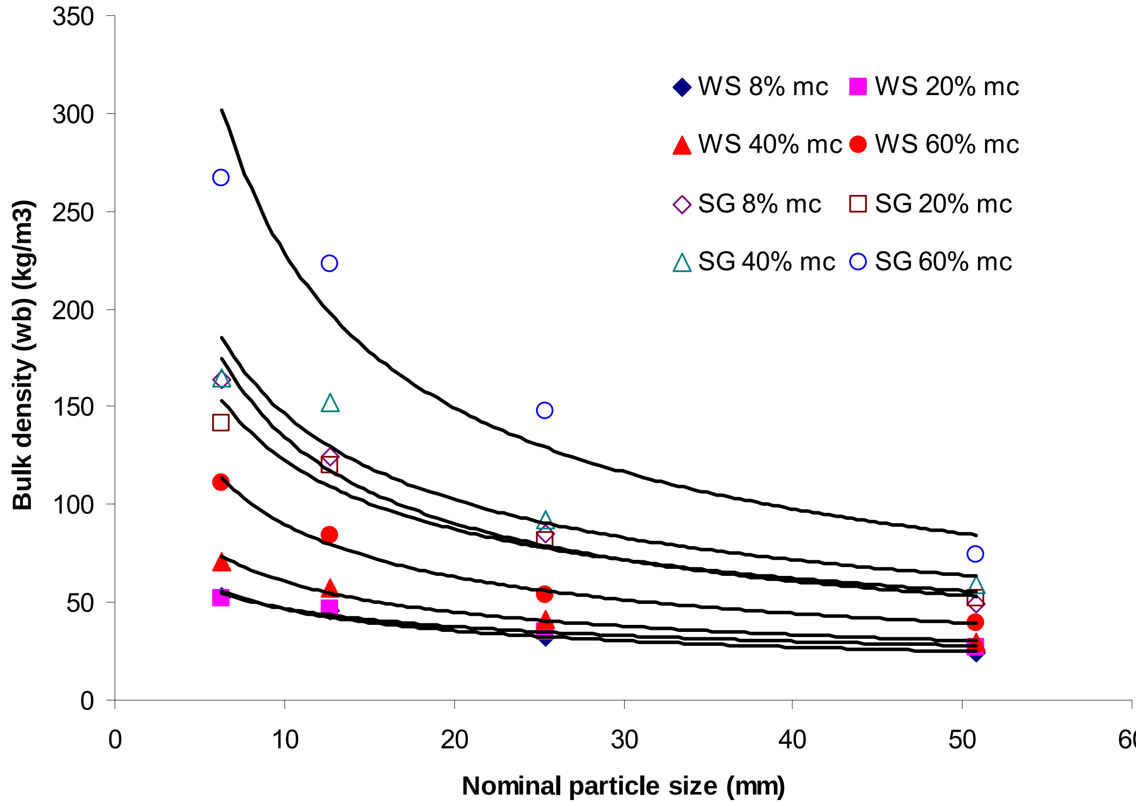

Figure 2: Bulk density (wb) of switchgrass (SG) and wheat straw (WS) at different sizes and moisture contents for the loose packing

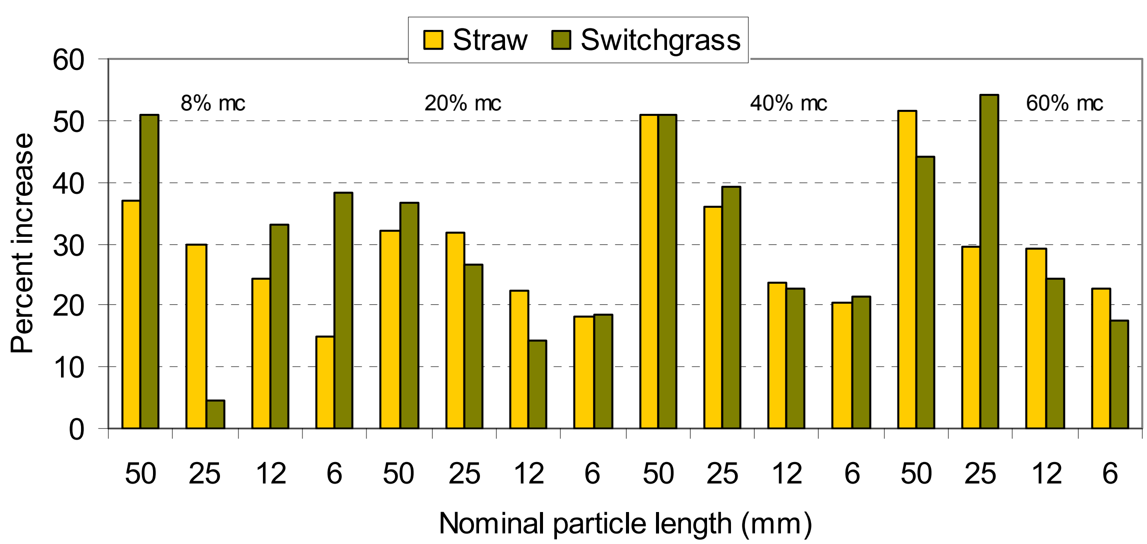

Figure 3: Percent increase in bulk density of straw and switchgrass as a result of tapping.

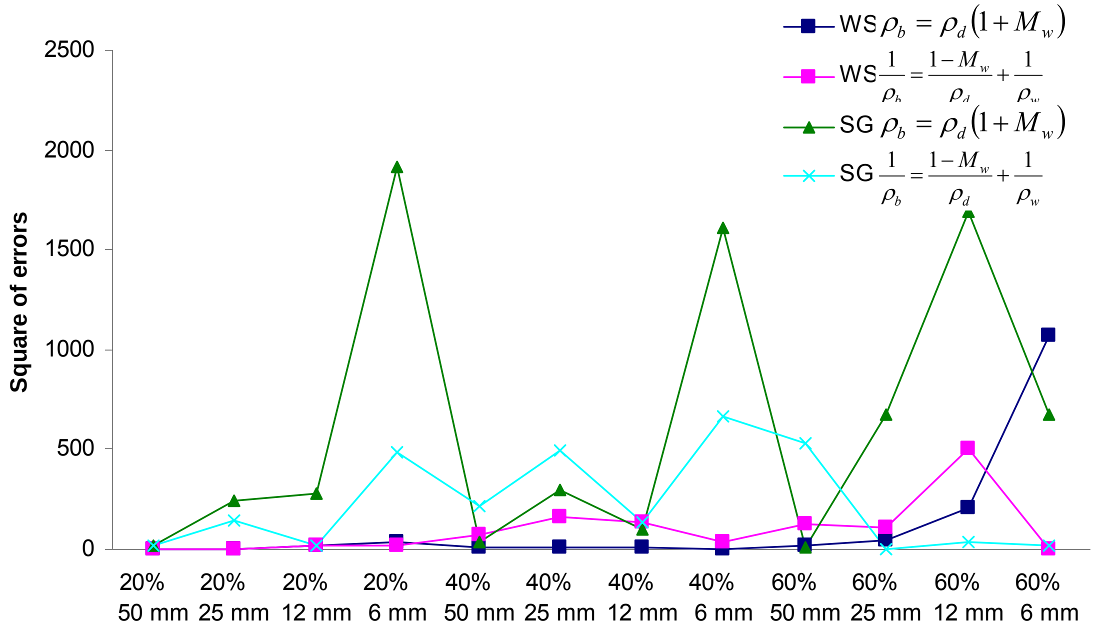

Figure 4: The square of errors of the values obtained from series and parallel equation for the prediction of wet based bulk density from dry based bulk density at different moisture content and particle sizes of both wheat straw (WS) and switchgrass (SG)

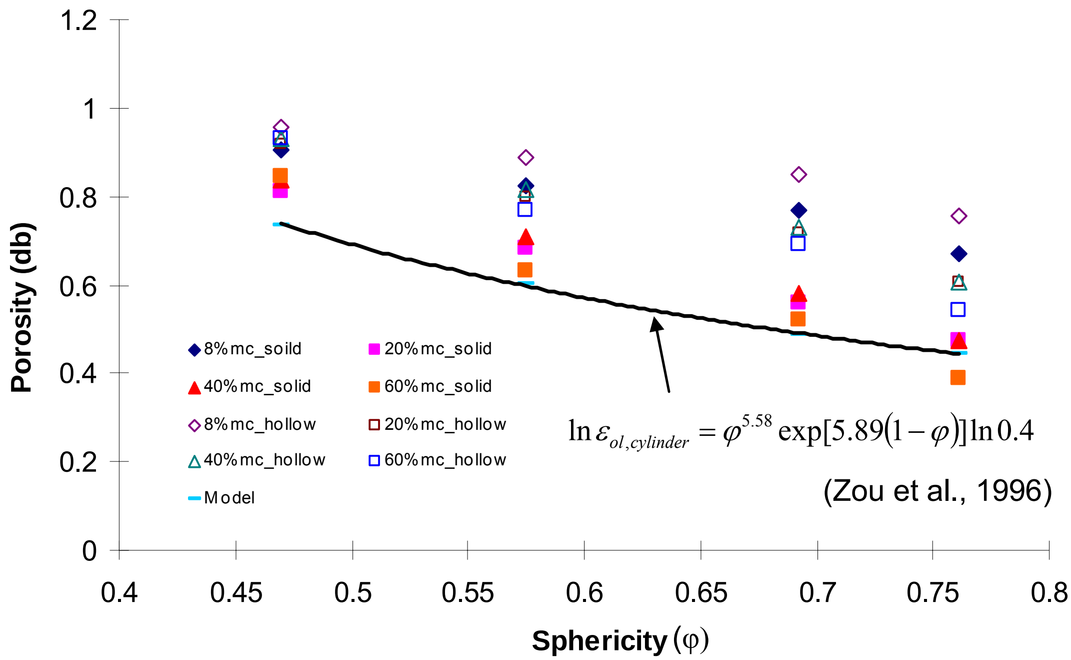

Figure 5: Bulk porosity (db) and shape of switchgrass relationship of loose packing at different moisture content assuming with solid and hollow cylindrical shapes respectively

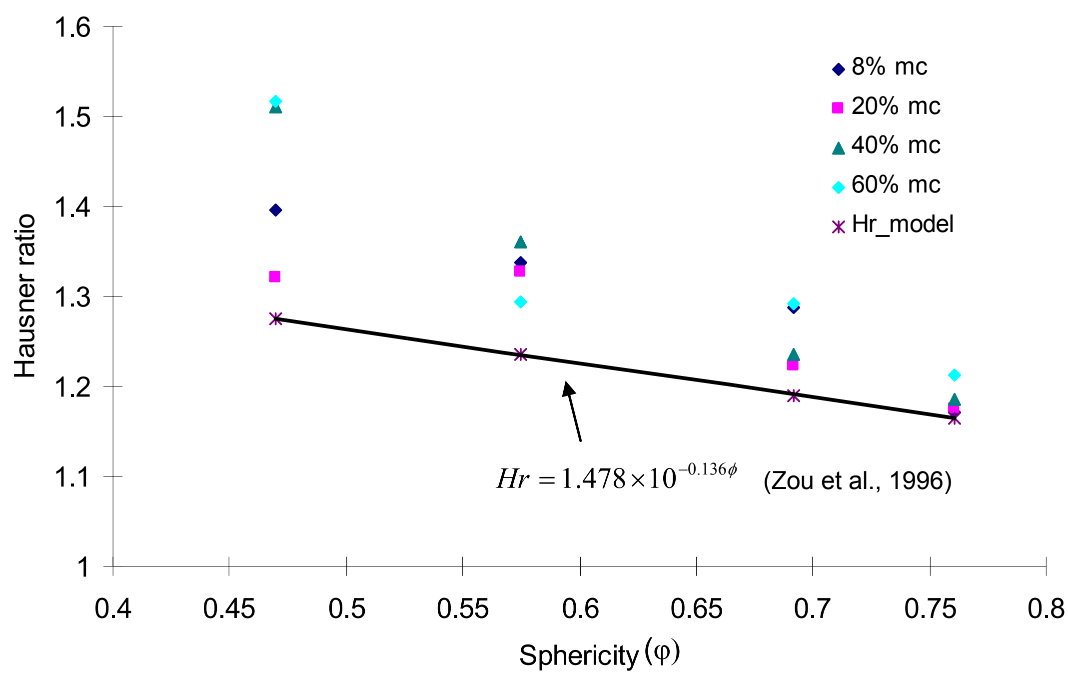

Figure 6: Hausner ratio – sphericity relationship of swtichgrass at different moisture content. Solid line represented the model developed by Zou et al. for solid equilateral cylindrical particles

Table 1: Physical dimensions of biomass target length and the cylindrical container dimensions for bulk density measurements

Type of biomass	Particle dimension	Cylindrical container dimension			Column diameter to particle length ratio
	Nominal Length (L) (mm)	Size	Diameter (D_T) (mm)	Height (H) (mm)	D_T/L
Wheat Straw	50.80	Large	246.00	250.00	5.38
	25.40	Large	246.00	250.00	10.75
	12.70	Medium	152.40	122.00	12.00
	6.35	Medium	152.40	122.00	24.00
Switchgrass	50.80	Large	246.00	250.00	5.38
	25.40	Large	246.00	250.00	10.75
	12.70	Medium	152.40	122.00	12.00
	6.35	Small	76.20	135.00	12.00

Table 2: Measurement of physical dimensions of oven-dried wheat straws and switchgrass (n=10)

Type of biomass	Length (L) (mm)			mass (m_p) (g)		Diameter (d_p) (mm)		Thickness (t) (mm)	
	Target	Measured Average	SD	Average	SD	Average	SD	Average	SD
Wheat Straw	50.8	56.598	2.708	0.029	0.010	2.648	0.419	0.146	0.053
	25.4	34.503	2.045	0.024	0.008	2.914	0.542	0.145	0.035
	12.7	17.172	1.432	0.010	0.003	2.952	0.346	0.125	0.025
	6.35	9.078	0.530	0.008	0.003	3.380	0.485	0.216	0.073
Switchgrass	50.8	51.774	1.990	0.064	0.019	2.600	0.581	0.340	0.108
	25.4	28.974	3.013	0.043	0.019	2.855	0.565	0.581	0.239
	12.7	14.721	1.079	0.025	0.015	2.916	0.562	0.486	0.152
	6.35	8.042	1.064	0.008	0.002	2.420	0.468	0.486	0.152

Table 3: Calculation of physical dimensions and shapes of wheat straws and switchgrass after oven drying (n=10) and for pycnometer particle volume and particle density (n = 3)

Type of biomass	Length (l) (mm)	Sphericity (φ)		Volume, hollow ($V_{p,\ hollow}$) (cm^3)		Volume, solid ($V_{p,\ solid}$) (cm^3)		Pycnometer particle volume (V_{pyc}) (cm^3)		Particle Density, hollow ($\rho_{p,\ hollow}$) (kg/m^3)		Particle Density, solid ($\rho_{p,\ solid}$) (kg/m^3)		Particle Density, Pycnometer (ρ_s) (kg/m^3)	
	Nominal	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
Wheat Straw	50.8	0.461	0.028	0.074	0.033	0.316	0.089	3.000	0.546	497.444	238.600	92.579	24.832	1057.614	212.996
	25.4	0.550	0.030	0.050	0.021	0.239	0.095	2.803	0.413	556.508	98.061	106.374	29.619	930.406	143.329
	12.7	0.670	0.028	0.021	0.005	0.118	0.027	0.502	0.051	519.050	103.200	83.517	16.679	1178.374	125.584
	6.35	0.793	0.020	0.023	0.010	0.083	0.025	0.678	0.033	394.971	93.199	92.933	29.263	1037.612	51.225
Switchgrass	50.8	0.470	0.034	0.169	0.085	0.285	0.130	10.990	0.710	543.838	159.076	241.061	72.690	629.745	41.851
	25.4	0.575	0.048	0.193	0.124	0.189	0.065	14.686	0.570	377.343	142.997	226.857	68.422	618.871	24.559
	12.7	0.692	0.038	0.080	0.038	0.101	0.035	2.845	0.007	453.515	165.863	244.047	89.096	656.866	1.604
	6.35	0.761	0.035	0.036	0.014	0.038	0.017	3.327	0.037	365.720	167.955	222.635	88.017	657.282	7.424

Table 4: Fitting of equations of the effect of particle moisture and particles size (x) of wheat straws and switchgrass on bulk densities (y) at wet basis in the power form of $y = ax^{-b}$

Type of biomass	Moisture content (wb%)	Bulk Density (wb)			Tapped Density (wb)		
		a	b	R^2	a	b	R^2
Wheat Straw	8	113.79	0.389	0.977	150.95	0.374	0.988
	20	98.80	0.323	0.973	97.88	0.246	0.998
	40	161.64	0.427	0.989	155.20	0.314	0.995
	60	290.71	0.510	0.991	261.04	0.371	0.996
Switchgrass	8	502.10	0.573	0.977	494.82	0.487	0.961
	20	378.10	0.489	0.963	397.28	0.426	0.940
	40	479.77	0.515	0.936	448.51	0.397	0.923
	60	938.03	0.613	0.933	938.67	0.516	0.935

Table 5: Raw data of bulk density measurement of biomass at different moisture contents and particle sizes

Type of biomass	Moisture content (wb%), n=3			Length (L), mm, n = 10	Loose fill mass and volume , n = 5			Tapped mass and volume, n = 5		
	Target	Measured average	SD	Average	Mass (g) Average	Mass (g) SD	Volume (m^3)	Mass (g) Average	Mass (g) SD	Volume (m^3)
Wheat Straw	8%	8.45	0.12	56.60	287.00	9.99	0.01188	548.10	3.65	0.01188
				34.50	383.15	19.12	0.01188	401.00	10.05	0.01188
				17.17	105.04	1.45	0.00230	139.65	1.68	0.00230
				9.08	121.48	1.93	0.00230	168.06	1.90	0.00230
	20%	21.59	0.71	56.60	322.00	6.67	0.01188	440.00	7.14	0.01188
		19.58	0.95	34.50	415.00	6.04	0.01188	525.40	7.64	0.01188
		20.65	0.60	17.17	98.20	6.50	0.00230	112.20	0.45	0.00230
		18.71	1.29	9.08	119.60	1.67	0.00230	141.60	1.67	0.00230
	40%	43.67	0.96	56.60	348.80	2.95	0.01188	526.60	7.33	0.01188
		48.07	2.36	34.50	491.60	4.04	0.01188	683.80	3.90	0.01188
		43.12	12.09	17.17	131.60	1.14	0.00230	161.60	1.14	0.00230
		41.43	5.02	9.08	162.60	0.89	0.00230	197.20	2.28	0.00230
	60%	58.57	1.11	56.60	634.00	9.99	0.01188	912.80	3.65	0.01188
		56.42	1.51	34.50	472.60	22.66	0.01188	728.40	7.89	0.01188
		64.55	2.70	17.17	192.80	6.02	0.00230	239.80	1.92	0.00230
		61.15	3.63	9.08	255.60	2.07	0.00230	300.00	1.58	0.00230
Switchgrass	8%	7.96	0.21	51.77	587.40	4.39	0.01188	804.00	8.15	0.01188
				28.97	1012.60	13.59	0.01188	1102.60	0.89	0.00996
				14.72	286.00	4.64	0.00230	355.60	2.41	0.00230

				8.04	50.00	--	0.00031	50.00	--	0.00027
	20%	23.04	1.48	51.77	616.80	5.63	0.01188	815.20	13.26	0.01188
		23.98	0.23	28.97	972.00	3.74	0.01188	1252.60	6.35	0.01163
		19.02	1.91	14.72	275.60	2.30	0.00230	337.20	2.59	0.00230
		22.76	2.03	8.04	55.00	--	0.00039	55.00	--	0.00033
	40%	42.95	3.56	51.77	704.40	10.16	0.01188	1063.40	11.28	0.01188
		39.23	3.20	28.97	1096.40	12.30	0.01188	1492.40	11.19	0.01188
		41.49	1.34	14.72	350.00	2.92	0.00230	432.60	2.41	0.00230
		36.01	1.25	8.04	67.00	--	0.00041	67.00	--	0.00034
	60%	57.63	0.70	51.77	881.40	40.93	0.01188	1336.00	31.60	0.01188
		54.72	0.38	28.97	1753.60	7.33	0.01188	2181.20	13.70	0.01142
		58.58	1.07	14.72	512.80	5.89	0.00230	662.60	4.28	0.00230
		59.42	3.54	8.04	101.00	--	0.00038	101.00	--	0.00031

Table 6: Comparison of measured and predicted wet based bulk density by equation 16

Type of biomass	Moisture content (wb%), n = 3			Particle length (mm), n = 10		Bulk Density (kg/m^3), n = 5		Tapped Density (kg/m^3), n = 5	
	Target	Measured average	SD	Average	SD	Measured	Predicted	Measured	Predicted
Wheat Straw	8%	8.45	0.12	56.60	2.71	24.16	25.21	33.75	35.16
				34.50	2.04	32.25	30.40	46.14	42.01
				17.17	1.43	45.67	39.50	60.72	53.87
				9.08	0.53	52.82	50.06	73.07	67.38
	20%	21.59	0.71	56.60	2.71	27.10	29.31	37.04	40.81
		19.58	0.95	34.50	2.04	34.93	34.46	44.23	47.55
		20.65	0.60	17.17	1.43	46.40	45.30	53.01	61.64
		18.71	1.29	9.08	0.53	52.00	56.02	61.57	75.25
	40%	43.67	0.96	56.60	2.71	29.36	40.33	44.33	55.92
		48.07	2.36	34.50	2.04	41.38	52.37	57.56	71.77
		43.12	12.09	17.17	1.43	57.22	62.08	70.26	83.94
		41.43	5.02	9.08	0.53	70.70	76.10	85.74	101.48
	60%	58.57	1.11	56.60	2.71	39.78	54.05	61.31	74.53
		56.42	1.51	34.50	2.04	53.37	61.79	76.84	84.36
		64.55	2.70	17.17	1.43	83.83	96.01	104.26	128.18
		61.15	3.63	9.08	0.53	111.13	110.46	130.43	145.49
Switchgrass	8%	7.96	0.21	51.77	1.99	49.44	53.78	67.68	72.92
				28.97	3.01	85.24	73.44	110.73	94.49
				14.72	1.08	124.35	104.62	154.61	126.72
				8.04	1.06	163.66	141.79	186.52	163.03

	20%	23.04	1.48	51.77	1.99	51.92	63.65	68.62	85.98
		23.98	0.23	28.97	3.01	81.82	87.56	108.56	112.16
		19.02	1.91	14.72	1.08	119.83	117.23	146.61	141.57
		22.76	2.03	8.04	1.06	141.48	164.48	166.14	188.38
	40%	42.95	3.56	51.77	1.99	59.29	83.99	89.51	112.60
		39.23	3.20	28.97	3.01	92.29	107.18	125.62	136.47
		41.49	1.34	14.72	1.08	152.17	155.27	188.09	185.85
		36.01	1.25	8.04	1.06	165.11	191.99	195.66	218.84
	60%	57.63	0.70	51.77	1.99	74.19	109.89	112.46	145.91
		54.72	0.38	28.97	3.01	147.61	138.76	191.09	174.98
		58.58	1.07	14.72	1.08	222.96	206.11	288.09	243.82
		59.42	3.54	8.04	1.06	266.52	272.56	323.10	306.40