Bioresource Technology 101 (2010) 6528–6537

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Simple and inexpensive method of wood pellets macro-porosity measurement

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ARTICLE INFO

Article history:
Received 19 November 2009
Received in revised form 6 March 2010
Accepted 11 March 2010
Available online 3 April 2010

Keywords:
Biomass
Density
Physical property
Porosity
Wood pellet

ABSTRACT

A novel simplified stereometric measurement method for determining the macro-porosity of wood pellets through geometrical approach was successfully developed and tested. The irregular ends of pellets of circular cross-section were sanded flat so that their geometry becomes cylinder and their volumes evaluated using mensuration formula. Such formed cylindrical pellets were loose or tap filled to selected volumes to evaluate the macro-porosity and the constant specific weight. The method was extended to evaluate actual wood pellets properties. Overall macro-porosity of actual wood pellets was determined as $41.0 \pm 2.5\%$ and $35.5 \pm 2.7\%$, mean bulk density as 670 ± 29 kg m^{-3} and 731 ± 31 kg m^{-3}, and classified as "Class-3:Medium" and "Class-3&4:Medium to Low" for loose and tapped fills, respectively. Hausner ratio and Carr's compressibility index classify wood pellets as "freely flowing." The developed stereometric method can be used as a handy inexpensive laboratory procedure to estimate the macro-porosity of different types and makes of wood pellets and other similar packaged materials.

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1. Introduction

Wood pellets are energy densified product from the viable renewable byproduct industries that caters to the clean energy needs nationally and internationally. For instance, wood pellets bio-fuel industry of Canada, with total sales of $\$2 \times 10^5$, while catering European Union nations, United States, and local demands, it helps in vitalizing the economy of local community (Wood Pellets Association of Canada, 2009). Wood pellets mostly made from the saw dust of lumber industry symbolize complete utilization as well as value addition of wood wastes at their best. Wood pellets allow automatic feeding and thus improved combustion control even for domestic and small-scale applications (Hamel and Krumm, 2008; Rabier et al., 2006).

Physical properties of wood pellets establish their quality. The physical properties that generally used to describe the integrity of the wood pellets are durability, bulk density, and porosity. The porosity of wood pellets, expressed in percentage, can be defined as the ratio of volume of voids to the total filled volume. The voids volume can be divided into (i) a major volume of voids existing among the pellets (outside) when they are held in bulk, and (ii) a minor volume corresponding to the collection of minute pores, cracks, and channels present inside pellet solids. The inclusion or exclusion of the pellet solids pore volume, further classifies porosity as total-porosity and apparent porosity (also known as bulk porosity/seed porosity/macro-porosity), respectively.

While measurement of wood pellet porosity is central in the design of storage silos and bunkers, and transportation containers, the porosity also influences the heat and mass transfer during combustion, and off-gas emissions. Furthermore, porosity has an influence on bulk density and on combustion properties of pellets and briquettes (heat conductivity, burning time, and rate of degasification). The porosity of packed wood pellets depends on a number of factors, such as particle size distribution, particle shape, shaking or pressing of the bed, and particle shrinking due to chemical conversion or agglomeration. Decrease in the porosity increases the interstitial airflow velocity and bring changes in heat and mass transfer conditions and ultimately influencing the combustion parameters, such as burning rate, efficiency, and emissions (Hamel and Krumm, 2008). Reported literature on porosity of biomass and wood pellets were highly limited, however several publications on porosity agricultural grains can be readily found.

As the wood pellet is actually a compacted form of saw dust particles bonded by pressure and heat, microscopic pores and

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0960-8524/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.biortech.2010.03.034

channels cannot be avoided. Availability of these micro-pores and wood particle interaction characteristics with liquid make wood pellets hygroscopic. This hygroscopicity of the wood pellets rules out the possibility of using the simple water/liquid displacement method. The liquid penetration into these interstitial channels making the pellets swell would interfere with the volume measurement thereby affecting the porosity determination. The hygroscopic properties of pellets not only act on the volume of the sample but also influence its mass (Rabier et al., 2006).

Measurement of mass in porosity measurement procedure is easy, but the volume determination is relatively not straightforward and has several associated uncertainties. Existing methods of air/gas displacement use the working medium under pressure to determine the solids density, hence utilize expensive measurement devices with accompanying instrumentation (e.g. digital gas comparison pycnometer). In such devices, since the working medium was applied under pressure during measurement, the medium enters inside the solid matrix of the pellets and saturates the minute interstitial pores or channels inside individual pellets (micro-porosity) as well as the void space among pellets (macro-porosity) thereby correlates only to the total pore volume.

Most of the reported literature on porosities used the gas pycnometer. The gas pycnometer also requires accurate mass measurements of pellets to evaluate the specific weight (true density or solids density), while the true solids volume of pellets determined under gas pressure. Fasina (2007a) reported the misrepresentation of particle density by various researchers without making distinction between true density and apparent/seed/envelope density, and these densities may differ by as much as 26%. The inclusion/exclusion of micro-porosity in the calculation forms the basis for this discrepancy. They concluded that the gas pycnometer measures only the true density (pellet solid volume excluding internal micro-pores), and other methods, such as envelope density analyzer and stereometric measurement methods measures only the apparent density (whole pellet volume including internal micro-pores) of the materials.

In this research, a simple novel method of stereometric measurements of wood pellets to determine the macro-porosity (apparent porosity), through geometrical approach was proposed. The macro-porosity can be considered as the most significant component of total-porosity that has ready access to gas interaction. This macro-porosity has direct application in the design of storage, handling, and transportation systems, since the micro-porosity does not influence the physical holding volume of the pellets. The proposed geometrical approach intends to determine the whole pellet volume (internal micro-pores included) by forming the pellets to conform a geometrical shape and then applying the analytical mensuration formula to evaluate their volume directly. The circular cross-section and cylindrical shape of the commercial wood pellets are advantageously utilized for this stereometric method. With the evaluated volume and mass, the specific weight of the formed pellets (apparent density) can be determined. This specific weight can be applied to measure the macro-porosity of actual wood pellets in bulk. This novel method is envisioned to be simple and inexpensive, as it uses only commonly available laboratory glassware and devices. The objectives of this research were to:

1. Develop a stereometric measurement geometrical method of determining the macro-porosity of wood pellets.
2. Determine the macro-porosity, specific weight, and bulk density of wood pellets with different fill volumes and fill methods (loose and tapped).
3. Evaluate the correlation between physical parameters as well as the effect of fill volume and fill method on macro-porosity and bulk density of wood pellets.
4. Make a cursory comparison of the specific weights based on the developed geometrical method with that of the gas pycnometer.

2. Methods

2.1. Materials

Softwood pellets (100%, Princeton Co-Generation Corp., Princeton, BC, Canada) were used as the test material. These commercial pellets come in 18.14 kg (40 lb) bags and were stored in the laboratory (22 °C, 55% RH) until experiments. Pellets had a uniform circular cross-section (1/4″∅) with straight axis making them cylindrically shaped. Ends of the pellets were irregular (Fig. 1a) due to natural breakage of the pellets while extruded out of the forming die.

Moisture content of the wood pellets was measured following the ASABE Standards, S358.2 (2008). This procedure obtained the bone dry mass of pellet samples using a hot oven at 103 °C and 24 h. The determined moisture content of the pellet samples with four replications was 7.51 ± 0.01% wet basis (w.b.).

Fig. 1. Softwood pellets used in the experiments: (a) actual pellets with the irregular breakaway ends but showing perfect cylindrical body, (b) cylindrical pellets prepared by sanding the ends, and (c) formed cylindrical pellets showing identification numbers and arranged in groups of 10 for testing.

2.2. Preparation of cylindrical pellets

The proposed novel idea, in essence, is taking advantage of the cylindrical shape of the pellet body and manipulating only the irregular ends, so that it conforms to a perfect cylindrical shape. Then the volume of such formed pellets can be directly evaluated from the geometric mensuration formula. Fine emery paper (mesh 500) was used to rub off the ends manually so that the ends were flat and perpendicular to the length axis (Fig. 1b). Such sanded ends flattened wood pellets will be refferred as "cylindrical pellets" and that with broken ends as "actual pellets" hereafter. Randomly drawn pellet samples that reflect the existing size variation were used for preparing the cylindrical pellets. During sanding of ends on the emery paper, some pellets broke and those were discarded. About 620 cylindrical pellets were prepared. Serial numbers identified the cylindrical pellets (Fig. 1c) for repeated use.

Digital calipers (Mastercraft, 0.01 mm accuracy; Great Star Tools Company, Incorporation, China) measured the length of cylindrical pellets, and the measurements were recorded against their identification numbers. Since the diameters of the pellets were uniform (1/4″∅), only 30 random measurements were made and the mean value of 6.532 ± 0.065 mm was used in the calculations.

2.3. Loose and tapped macro-porosity and bulk density measurement of cylindrical and actual pellets

Graduated glass beakers (600 ml, 90 mm ∅ × 125 mm height, Kimax Kimble, USA; and 3000 ml, 155 mm ∅ × 213 mm height, Pyrex®, USA). Cylindrical pellets were filled to various volumes considered, such as 100, 200, 300, 400, and 500 ml, using a 600 ml beaker. For actual pellets, in addition to the above volumes, 1000, 1250, 1500, 2000, and 2500 ml were considered using a 3000 ml beaker.

While filling, randomly selected bulk of pellets were poured from a height of approximately 100 mm from the brim of the beakers. Care was exercised during filling so that the top filled surface was flat and conformed to the selected experimental volume. Such method of filling checked against the beaker graduation, avoided the need for measuring the height of fill. This procedure represents the loose filled condition of pellets.

Tapping the pellet filled beaker on hard wooden surface simulated the settling behavior of the pellets in shaking or vibration during transport. Fifty taps with a tap height of about 20 mm (Chevanan et al., 2008) produced a stable settled state of pellets. Top-loading digital balance (0.01 g readability, 1000 g capacity, ACB plus – 1000, Adam Equipment Incorporation, USA) determined the pellet mass directly after nullifying the beaker mass (Fig. 2). The procedure of filling, tapping, and mass measurements were common for both the cylindrical and actual pellets. All the measurements were replicated for five times.

Fig. 2. Wood pellets dimensions measurement using digital caliper and mass measurement for loose and tapped densities determination.

2.4. Calculation of macro-porosity, bulk density, and related physical parameters of cylindrical and actual wood pellets

Macro-porosity is defined as the percentage of volume of voids among the pellets when they are held in bulk to the overall fill volume. Although the measurement of voids volume cannot be readily made by simple means, the fill volume can be easily obtained from the graduations or dimensions of the container. However, for cylindrical pellets the voids volume was easily obtained indirectly by deducting the pellets volume from the fill volume. The volume of cylindrical pellets using geometrical mensuration formula is expressed as:

$$V_c = \frac{\pi}{4} d^2 \sum_{i=1}^{n} l_i, \tag{1}$$

where V_c is the cylindrical pellets volume (m^3), d is the mean diameter (m), l_i is the variable length (m) of the ith pellet, and n is the number of pellets used in the fill.

The macro-porosity (ϕ_c) expressed from the fill volume (V_f) and cylindrical pellet volumes in percentage as:

$$\phi_c = \frac{V_f - V_c}{V_f} \times 100. \tag{2}$$

For the cylindrical wood pellets the specific weight is calculated from:

$$W_{sc} = \frac{W_c}{V_c}, \tag{3}$$

where W_{sc} is the specific weight of cylindrical wood pellets (kg m^{-3}), and W_c is the cylindrical wood pellets mass (kg).

Similarly, for actual wood pellets the specific weight is expressed as:

$$W_{sa} = \frac{W_a}{V_a}, \tag{4}$$

where W_{sa} is the specific weight of actual wood pellets (kg m^{-3}), W_a is the actual wood pellets mass (kg), and V_a is the actual wood pellets volume (m^3) – an unknown quantity.

Since the specific weights (Eqs. (3) and (4)) of wood pellets irrespective of their end profile or irregularities will be the same, as they were extruded from the same pelletizers utilizing similar input materials. The unknown actual wood pellet volume can be obtained from the similarity of specific weights. A similar expression for macro-porosity of actual pellets (ϕ_a) can be obtained by replacing V_c for V_a following the Eq. (2). From that expression, eliminating V_a, by equating specific weights from Eqs. (3) and (4), and expressing in terms of other easily measurable parameters (V_c, W_a, and W_a), the macro-porosity of actual wood pellets is evaluated as:

$$\phi_a = \frac{V_f - (W_a/W_{sc})}{V_f} \times 100. \tag{5}$$

The loose and tapped densities of wood pellets are given as:

$$\rho_l = \frac{W_l}{V_l}, \tag{6}$$

$$\rho_t = \frac{W_t}{V_t}, \tag{7}$$

where ρ_l and ρ_t are the bulk densities (kg m^{-3}), W_l and W_t are the masses (kg), V_l and V_t are the volumes (m^3) of pellets in loose and tapped fill conditions, respectively. The loose bulk density is also known as poured bulk density. It can be recollected that the various volumes namely V_f, V_l, and V_t are simply the made up final filled volumes (independent variable) of pellets in specific fill conditions.

Hausner ratio (HR) expressed in decimals, a value often correlated to material flowability, is defined as the ratio of a materials tapped bulk density to its loose bulk density (Grey and Beddow, 1969; Garcia et al., 2007), and is given as:

$$\mathrm{HR} = \frac{\phi_t}{\phi_l}, \tag{8}$$

where ϕ_t and ϕ_l are the porosity values (%) of pellets in tapped and loose fill conditions, respectively.

Carr's compressibility index (I_c) expressed in percentage, another flowability indicator (Carr, 1965; Schüssele and Bauer-Brandl, 2003), is defined as:

$$I_c = \frac{\phi_t - \phi_l}{\phi_t} \times 100. \tag{9}$$

From the definition of Hausner ratio (Eq. (8)) and Carr's compressibility index (Eq. (9)), both these quantities can be expressed in terms of the other as:

$$I_c = \left(1 - \frac{1}{\mathrm{HR}}\right) \times 100. \tag{10}$$

2.5. Comparison between macro- and total-porosity with pycnometer measurements

To compare the macro-porosity with the total-porosity (micro-porosity included), a gas pycnometer (Multipycnometer™, Quantachrome instruments, Florida, USA) was used. The pycnometer measured the solids density of cylindrical wood pellets. Two samples of each containing 40 labeled cylindrical wood pellets were tested. Total mass of these pellets were 24.95 ± 0.58 g. The largest sample cell ($\approx 150{,}000$ mm^3) of the pycnometer was used in the measurement. Five repeated measures on each samples were performed. The true density (solids density) measured was used to determine the porosity using the relationship: total-porosity = 1 − (bulk density true density).

2.6. Data analysis

Statistical data analyses were carried out to establish the correlation among the different variables, obtain useful regression equations from the most influencing variables, study the effect of fill volume, and fill method on the physical parameters for both fill methods. The statistical test of significance of overall means was also performed. Both cylindrical and actual wood pellets data were analyzed. SAS (2008) procedures, such as CORR, TTEST, and macros *%macro reg* and *%macro mmaov* of Saxton (2003) analyzed the data.

3. Results and discussion

3.1. Physical properties of cylindrical wood pellets

3.1.1. Macro-porosity

The mean macro-porosity of cylindrical wood pellets (Eq. (2)) among the fill volumes (100–500 ml) varied from 39.4% to 44.9% and 34.0% to 40.4%, while the overall means were $42.6 \pm 2.4\%$ and $36.9 \pm 2.7\%$ for loose and tapped fill, respectively (Fig. 3). Among particulate materials, soils exhibit similar wide variation in porosity. One classification of dry soils (Anonymous, 1979), described porosity values in the range of 35% to 45% as "Medium" and grouped under "Class-3," 30% to 35% as "Low" and "Class-4," <30% as "Very low" and "Class-5." Based on this classification, the porosity of cylindrical wood pellets belongs to "Class-3" and described as "Medium." The macro-porosity decreased gradually with increased fill volumes. Consolidation effect expected with larger amounts of sample material with increased fill volumes might be the reason for the observed decrease.

Another reason for the observed variation was the possible fairly constant allowable error in the manual volume measurement by eye judgment. This would have greater impact when the fill volume is smaller than otherwise. This explained the observed longer error bars with 100 ml, and the effect reduced as the fill volume increased (Fig. 3). From the mean data, tapping of cylindrical wood pellets produced a macro-porosity reduction of $5.70 \pm 1.96\%$ among the fill volumes (100–500 ml).

3.1.2. Bulk density

The mean bulk density of loose fill (Eq. (6)) cylindrical wood pellets varied between 606 and 686 kg m^{-3} with overall mean of 650 ± 32 kg m^{-3}, while that of tapped fill (Eq. (7)) between 677 and 749 kg m^{-3} with overall mean of 717 ± 31 kg m^{-3} (Fig. 4). These bulk density values, being greater than most of the

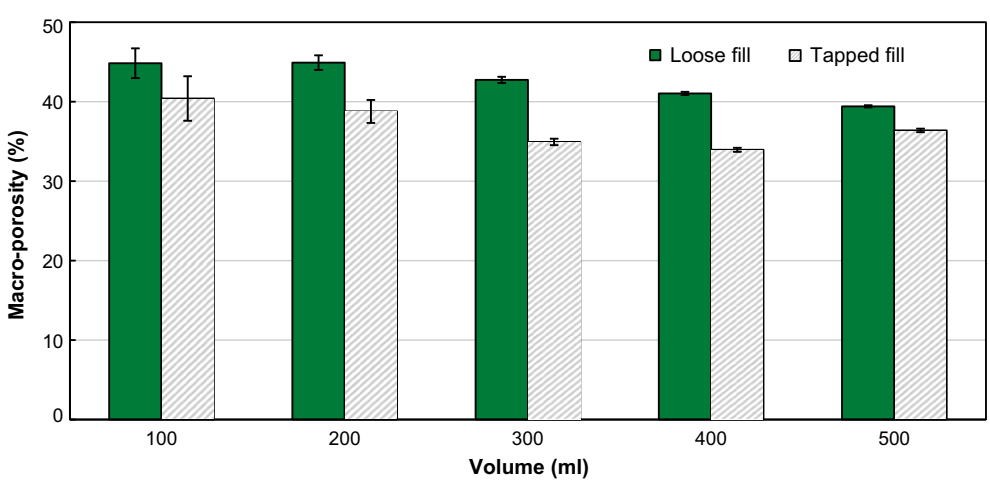

Fig. 3. Cylindrical wood pellets macro-porosity at loose and tapped fills.

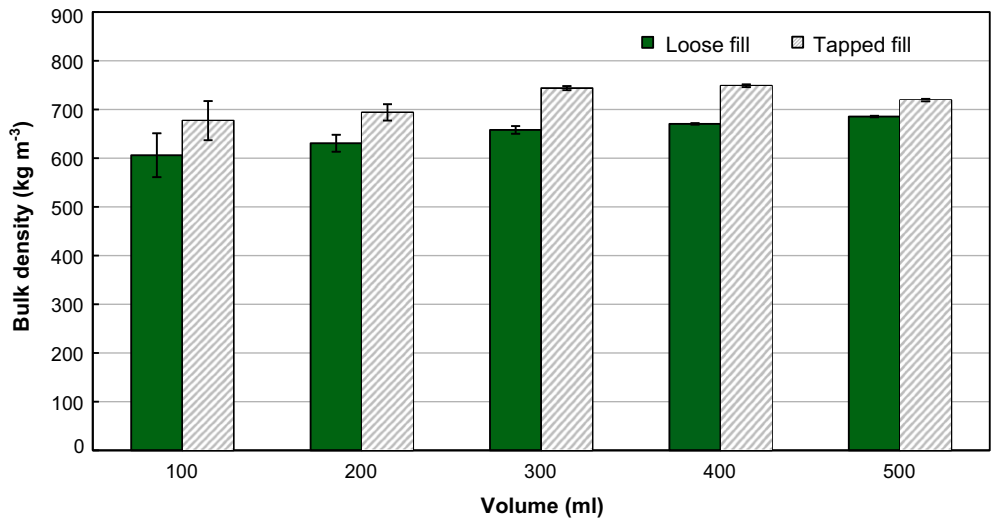

Fig. 4. Cylindrical wood pellets bulk density at loose and tapped fills.

agricultural grains (< 600 kg m^{-3}), indicate that the machine extruded wood pellets undergo good compaction resulting in a dense product. The good consolidation with increased volumes of fill (100–500 ml) explained the slight gradual increasing trend in bulk density. The variation among the replications diminished as well with increased quantity of sample. Tapped fills showed the obvious increase in bulk density over loose fill. Tapping increased the bulk density of loose fill on average by 66 ± 20 kg m^{-3}.

3.1.3. Specific weight

Mean specific weight of cylindrical wood pellets (Eq. (3)) at different fill volumes (100–500 ml) and fill methods varied from 1099.5 to 1149.3 kg m^{-3}, with a mean of 1133.9 ± 13.6 kg m^{-3}. However, the specific weights ranged closely from 1130.7 to 1135.6 kg m^{-3} for fill volumes in the range of 300–500 ml and the standard deviation in this range was less than 2 kg m^{-3}. Because specific weight is a material property that is independent of fill method, consolidation, and orientation or arrangement of individual particles in the bulk, the variation of specific weight of pellets is less. The cylindrical wood pellets mean specific weight value of 1133.89 kg m^{-3} was used as the constant factor to evaluate the porosity of actual wood pellets (Eq. (5)). Increased specific weight positively influences the efficient pellets handling and transportation. Pellets specific weight depends on the characteristics of the input material and can be altered only a little by the machine operating conditions within the allowable range of pelletization.

3.1.4. Correlation among physical parameters

The Pearson correlation coefficients (r) among the physical parameters of cylindrical wood pellets (Table 1) were used to identify the influentially correlated parameters for developing macro-porosity and bulk density models. Bulk density showed highly significant correlation ($0.81 \leqslant r \leqslant 0.82; P < 0.0001$) with fill volume, original volume, and mass for loose fill; however, for tapped fill the r values were reduced ($0.60 \leqslant r \leqslant 0.64; 0.001 \leqslant P \leqslant 0.008$). Macro-porosity displayed highly significant negative correlation ($-0.77 \leqslant r \leqslant -0.91; P < 0.0001$) with fill volume, original volume, mass, and bulk density for loose fill; however, the correlation got reduced for tapped fill ($-0.67 \leqslant r \leqslant -0.93$; $< 0.0001 \leqslant P \leqslant 0.0002$).

3.1.5. Effect of fill volume and fill method on physical parameters

Effect of fill volume on the measured and derived physical properties was analyzed using mean separation for both loose and tapped fills (Table 2), and this fill volume effect is an indicator of suitability of data in scaled-up scenarios. The derived bulk density and macro-porosity, although considered a constant material property, showed some difference in means with the fill volumes. The smallest 100 ml fill volume was clearly separated from 300 ml or

Table 1
Pearson correlation coefficients ($r, (P > |r|)$) of loose and tapped fill physical parameters with cylindrical wood pellets ($N = 25$).

Parameter	Loose fill						Tapped fill					
	Fill volume	Actual volume	Mass	Bulk density	Specific weight	Macro-porosity	Fill volume	Actual volume	Mass	Bulk density	Specific weight	Macro-porosity
Fill volume	1.0000 (–)						1.0000 (–)					
Actual volume	0.9992 (< 0.0001)	1.0000 (–)					0.9987 (< 0.0001)	1.0000 (–)				
Mass	0.9995 (< 0.0001)	0.9997 (< 0.0001)	1.0000 (–)				0.9984 (< 0.0001)	0.9998 (< 0.0001)	1.0000 (–)			
Bulk density	0.8133 (< 0.0001)	0.8111 (< 0.0001)	0.8238 (< 0.0001)	1.0000 (–)			0.5987 (0.0016)	0.6292 (0.0008)	0.6378 (0.0006)	1.0000 (–)		
Specific weight	0.2054 (–0.3247)	0.1895 (–0.3643)	0.2137 (–0.305)	0.6542 (–0.0004)	1.0000 (–)		–0.0791 (0.7069)	–0.0780 (0.7109)	–0.0588 (0.7801)	0.3601 (0.077)	1.0000 (–)	
Macro-porosity	–0.9025 (< 0.0001)	–0.9130 (< 0.0001)	–0.9095 (< 0.0001)	–0.7727 (< 0.0001)	–0.0255 (0.9037)	1.0000 (–)	–0.6706 0.0002	–0.7027 (< 0.0001)	–0.7047 (< 0.0001)	–0.9388 (< 0.0001)	–0.0168 (0.9364)	1.0000 (–)

Table 2
Effect of fill volume of cylindrical wood pellets by mean separation analysis.

Fill method	Fill volume (mm^3)	Pellet volume (mm^3)	Mass (g)	Macro-porosity (%)	Bulk density (kg m^{-3})
Loose	100	55137.79 ± 1.82 E	60.47 ± 0.13 E	44.81 ± 0.06 A	604.70 ± 0.40 C
	200	110161.24 ± 2.58 D	126.10 ± 0.18 D	44.91 ± 0.06 A	630.52 ± 0.41 BC
	300	171763.38 ± 3.22 C	197.40 ± 0.23 C	42.74 ± 0.06 B	657.99 ± 0.42 AB
	400	235855.92 ± 3.77 B	268.17 ± 0.27 B	41.04 ± 0.06 C	670.42 ± 0.42 AB
	500	302950.76 ± 4.27 A	342.75 ± 0.30 A	39.41 ± 0.06 D	685.50 ± 0.42 A
Tapped	100	59546.43 ± 2.64 E	67.61 ± 0.11 E	40.33 ± 0.10 A	676.09 ± 0.34 C
	200	122422.46 ± 3.78 D	138.77 ± 0.16 D	38.75 ± 0.10 AB	693.85 ± 0.35 BC
	300	195192.27 ± 4.78 C	223.15 ± 0.20 C	34.93 ± 0.09 CD	743.84 ± 0.36 A
	400	264209.45 ± 5.56 B	299.49 ± 0.23 B	33.95 ± 0.09 D	748.72 ± 0.36 A
	500	318071.97 ± 6.10 A	359.63 ± 0.25 A	36.38 ± 0.09 BC	719.26 ± 0.36 AB

Note: The values represent estimates of mean ± estimates of standard error.
Dissimilar mean separation group labels (A–E) represent significant difference ($P < 0.05$).

greater. The combination of the effects of consolidation and volume measurement error, might be the reason for the observed mean groups' variation. Furthermore, there is a clear indication that with greater and closer fill volumes the bulk density and macro-porosity tend to be statistically similar.

Between loose and tapped fills, with reference to bulk density and macro-porosity, the loose fill tend to produce slightly more separated mean groups than the tapped fill. The analyses indicate clear statistically significant ($P < 0.05$) mean difference of original volume and mass of wood pellets (different group labels: A–E). This logical trend is expected to be similar to actual pellets and continue for other volumes as well, unless the fill volumes were too close.

Mean separation results of cylindrical wood pellets, with fill method as the classification variable, revealed that pellet volume, mass, bulk density, and macro-porosity were significantly ($P < 0.05$) different for loose and tapped fills (analysis results not shown). The mean values of various parameters can obtained from respective results sections and Table 2. These results indicate consolidation of pellets by tapping significantly increased the bulk density as well as reduced the macro-porosity, which is desirable from the handling and transportation standpoints.

3.1.6. Hausner ratio and Carr's compressibility index

The Hausner ratio varied from 1.05 to 1.13, with a mean of 1.10 ± 0.03 among the different fill volumes. The Carr's compressibility index among studied fill volumes varied from 4.69% to 11.54%, with a mean of $9.26 \pm 2.69\%$. Discussion on Hausner ratio and Carr's compressibility index of the wood pellets is deferred to Section 3.2.4.

3.2. Physical properties of actual wood pellets

3.2.1. Macro-porosity

The mean macro-porosity of actual wood pellets (Fig. 1a; Eq. (5)) among the various fill volumes considered (100–2500 ml) varied from 36.6% to 43.6% and 29.5% to 38.9%, with overall mean of $41.0 \pm 2.5\%$ and $35.5 \pm 2.7\%$ for loose and tapped fill, respectively (Fig. 5).

It would be interesting to compare the reported porosity values of particulate material from allied fields. The porosity of the granular material, such as agricultural grains and biomass pellets fall in a wide range of values; for example, Bambara groundnut seeds 20–24% (Mpotokwane et al., 2008), neam nuts 48–62% (Visvanathan et al., 1996), green gram 40.77–45.16% (Nimkar and Chattopadhyay, 2001), rice 47–66% (Corrêa et al., 2007), switchgrass 54–96% and chopped wheat straw 89–98% (Lam et al., 2007), peanut hull pellets 54–58% (Fasina, 2007b), poultry litter pellets 51–54% (McMullen et al., 2005), and wood pellets 43.6% (Melin et al., 2008). Again based on soil classification (Section 3.1.1), the loose filled wood pellets fall in "Class-3" with "Medium" description and tapped fill wood pellets belonged both "Class-3&4" with "Medium to Low" description.

The porosity value reported by Melin et al. (2008) for wood pellets was 43.6% that were transported through ocean vessel and was indirectly evaluated using a laboratory determined specific density value for pellets. Their method estimated the voids from the

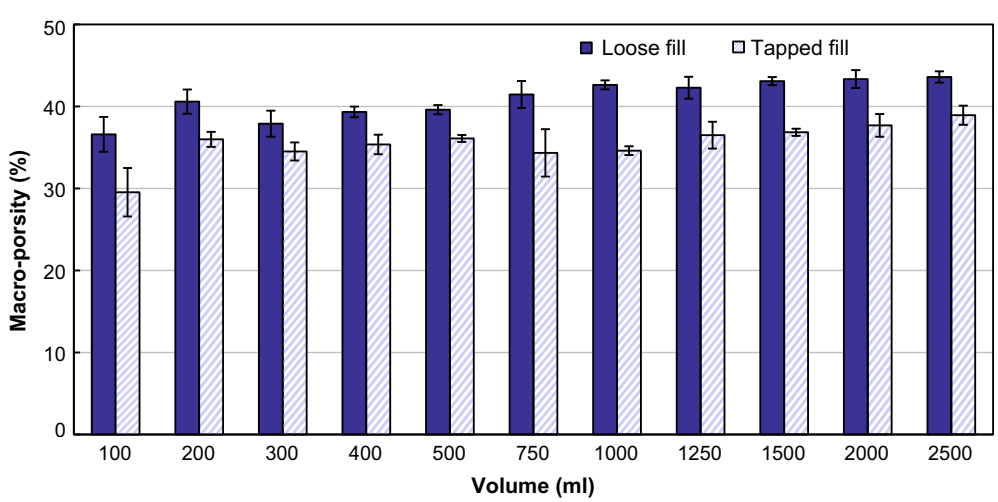

Fig. 5. Actual wood pellets macro-porosity at loose and tapped fills.

volume of ocean vessel cargo hatch (5473.6 m^3) by subtracting the volume of pellets (3086.1 m^3), obtained from the ratio of the weight of pellets (4,110, 674 kg) to the specific density (1332 kg m^{-3}). The macro-porosity values reported in the present study (29.5–43.6%) were coinciding or smaller than that reported by Melin et al. (2008). Since the laboratory method they used was gas displacement to obtain the specific density that accounted for inner pores of the pellet, tend to produce reduced solids volume and therefore increased specific density value, unlike the geometrical approach followed in the present study. It should be noted that the specific density in their method is very sensitive parameter. Following their procedure (Melin et al., 2008) and applying the specific weight of cylindrical wood pellets (inner pores not considered) from this study (1133.89 kg m^{-3}), the porosity of wood pellets in ocean vessel cargo hatch can be evaluated as 33.77%. This result shows a clear reduction in porosity from the reported 43.6%, which corroborates the results of this study. Thus the method developed in this research produces valid and accurate measurements.

Unlike the cylindrical wood pellets, the loose fill macro-porosity of actual wood pellets displayed a slight increase initially and then stabilization at increased fill volumes (Fig. 5). However, the tapped fill macro-porosity did not show any clear trend with the fill volumes. This observed behavior can be attributed to the existing differences between the cylindrical and actual wood pellets, such as the end profile of the pellets, and usage of increased fill volumes with actual wood pellets. Similar to cylindrical wood pellets, tapped fill on average produced a reduction of $5.45 \pm 1.56\%$ in macro-porosity with actual wood pellets when compared to loose fill.

In another correlation analysis determining the association of density and porosity of actual pellets, the derived parameters, such as loose fill macro-porosity, tapped fill macro-porosity, loose fill bulk density, and tapped fill bulk density, were well correlated and Pearson correlation coefficients ($r > \pm 0.73; P < 0.0001$) were statistically significant (results not shown).

The correlation results obtained for cylindrical wood pellet indicate that macro-porosity significantly related to fill volume, and mass (Table 1), and similar trend is also expected with actual wood pellets. It would be useful to develop simple regression equations of derived parameters, such as macro-porosity utilizing the easily measurable most significant pellet properties. Such regression equations of macro-porosity of actual wood pellets developed from the fill volume data of 500–2500 ml for loose fill are:

$$\text{Macro-porosity } (\%) = 40.028 + 0.0017 \times \text{Fill volume } (\text{mm}^3) \quad (R^2 = 0.72),$$

$$\text{Macro-porosity } (\%) = 39.964 + 0.0026 \times \text{Mass } (\text{g}) \quad (R^2 = 0.72).$$

And, that for tapped fill are:

$$\text{Macro-porosity } (\%) = 33.734 + 0.0020 \times \text{Fill volume } (\text{mm}^3) \quad (R^2 = 0.74),$$

$$\text{Macro-porosity } (\%) = 33.644 + 0.0032 \times \text{Mass } (\text{g}) \quad (R^2 = 0.75).$$

It should be noted that these models work well in the volume and mass ranges tested in the study.

3.2.2. Bulk density

Among the various fill volumes of actual wood pellets, the mean bulk density ranged between 640 and 719 kg m^{-3} with overall mean of 670 ± 29 kg m^{-3} for loose fill, and between 692 and 799 kg m^{-3} with overall mean of 731 ± 31 kg m^{-3} for tapped fill (Fig. 6). Melin et al. (2008) reported a bulk density of 751 kg m^{-3} at a moisture content of 5.8% w.b., which was found to be well within the observed range of bulk density in this study. Any variation can be attributed to material or species differences. Loose and tapped bulk densities exhibited a slight reduction with increased fill volume initially and stabilized later (Fig. 6). For actual wood pellets, the bulk density increase by tapping on average was 62 ± 18 kg m^{-3} with reference to loose fill.

Similar linear models developed for bulk density from the fill volume data of 500–2500 ml for loose fill are as follows:

$$\text{Bulk density } (\text{kg m}^{-3}) = 680.02 - 0.0189 \times \text{Fill volume } (\text{mm}^3) \quad (R^2 = 0.72),$$

$$\text{Bulk density } (\text{kg m}^{-3}) = 680.75 - 0.0299 \times \text{Mass } (\text{g}) \quad (R^2 = 0.72).$$

And the models for tapped fill are:

$$\text{Bulk density } (\text{kg m}^{-3}) = 751.38 - 0.0226 \times \text{Fill volume } (\text{mm}^3) \quad (R^2 = 0.74),$$

$$\text{Bulk density } (\text{kg m}^{-3}) = 752.40 - 0.0359 \times \text{Mass } (\text{g}) \quad (R^2 = 0.75).$$

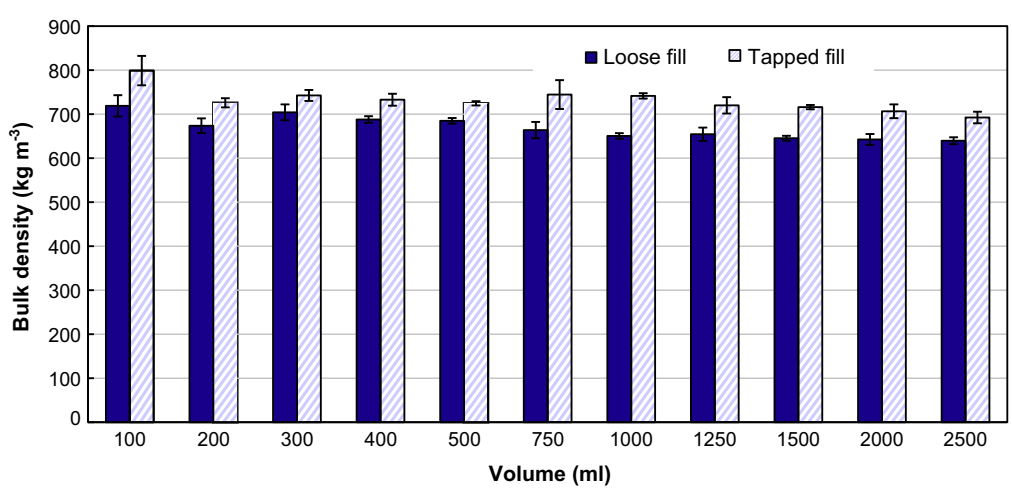

Fig. 6. Actual wood pellets bulk density at loose and tapped fills.

Table 3
Mean separation analysis of actual wood pellets based on fill volume.

Fill volume	Loose fill		Tapped fill	
Volume (mm^3)	Macro-porosity (%)	Bulk density (kg m^{-3})	Macro-porosity (%)	Bulk density (kg m^{-3})
100	36.55 ± 0.08 F	718.58 ± 0.25 A	29.42 ± 0.12 C	798.42 ± 0.30 A
200	40.57 ± 0.09 BCD	673.44 ± 0.24 CD	35.98 ± 0.13 AB	725.71 ± 0.29 BCD
300	37.87 ± 0.09 EF	703.95 ± 0.24 AB	34.50 ± 0.13 B	742.48 ± 0.29 BC
400	39.33 ± 0.09 DE	687.84 ± 0.24 ABC	35.35 ± 0.13 AB	732.78 ± 0.29 BC
500	39.60 ± 0.09 CDE	684.80 ± 0.24 BC	36.10 ± 0.13 AB	724.55 ± 0.29 BCD
750	41.43 ± 0.09 ABCD	663.57 ± 0.24 CDE	34.24 ± 0.12 B	743.94 ± 0.29 B
1000	42.63 ± 0.09 AB	650.50 ± 0.23 DE	34.61 ± 0.13 B	741.45 ± 0.29 BC
1250	42.27 ± 0.09 ABC	654.26 ± 0.23 DE	36.47 ± 0.13 AB	719.81 ± 0.28 BCD
1500	43.09 ± 0.09 AB	645.32 ± 0.23 DE	36.85 ± 0.13 AB	715.99 ± 0.28 BCD
2000	43.33 ± 0.09 AB	642.40 ± 0.23 E	37.67 ± 0.13 AB	706.36 ± 0.28 CD
2500	43.59 ± 0.09 A	639.56 ± 0.23 E	38.92 ± 0.13 A	692.30 ± 0.28 D

Note: The values represent estimates of mean ± estimates of standard error.
Dissimilar mean separation group labels (A–F) represent significant difference ($P < 0.05$).

These models indicate the bulk density of actual wood pellets is fairly constant and vary only a little with fill volume and mass. Biomass densification objective, in general, aiming at improving the bulk density, and this increased bulk density observed with tapped fills clearly demonstrates this objective. Increased bulk density of wood pellets also signify increased energy density and efficient handling and transportation logistics.

3.2.3. Effect of fill volume and fill method on physical parameters

Statistical mean separation method ($P < 0.05$) analyzed the effect of various studied fill volumes on bulk density and macro-porosity for both loose and tapped fills (Table 3). Although mean group labels were different, a clear trend of non-significant effect on adjacent fill volumes can be observed. Only five mean groups (A–E) for bulk density and six mean groups (A–F) for macro-porosity representing the 11 fill volumes substantiate this observation. Similar or overlapping mean group labels at higher volumes studied, such as 1000 ml clearly indicate the non-significant effect of fill volume on the bulk density and macro-porosity. Hence, it can be deduced that fill volumes will not affect the bulk density and macro-porosity when large quantities of wood pellets were handled, as followed in industrial operations.

The Students *t*-test comparison performed between loose and tapped fill methods of actual wood pellets, after pooling the data of all fill volumes, showed that the means differ significantly (Table 4). Tapping or vibration is the reason that enhanced the bulk density and reduced the macro-porosity.

Macro-porosity, in principle, occurs due to voids that appear while pellets are held in bulk because of pellets interaction and arrangement. To harness the benefits of reduction in macro-porosity, the voids should be manipulated by advanced methods to achieve better packing of pellets. Theoretical maximum limits in packing of cylindrical materials, such as wood pellets and corn stalks (Igathinathane et al., 2009) with their axis aligned parallel can be studied by circle packing theory (Weisstein, 2009).

Assuming uniform diameter, the two common methods of packing circles of uniform diameter are parallel and hexagonal. It can be visualized that in parallel arrangement the repeating feature is a square element whose side is the diameter of circle with four corners composed of quarter circles (one circle area), and that of hexagonal arrangement is an equilateral triangle element whose side is the diameter of circle with three corners composed of one sixth circle (half circle area). Therefore it can be shown that the ratio of void space to the whole geometry will be $1 - \pi/4 = 0.2146$ and $1 - \pi/(2\sqrt{3}) = 0.0931$ for parallel and hexagonal arrangements, respectively, which also indicate the theoretical maximum limits on packing density. This means a macro-porosity theoretical minimum limit of 21.46% in parallel and 9.31% in hexagonal packing arrangements are possible. These limits reveal a great potential of achievable reduction in macro-porosity as the determined values for actual wood pellets were in the range of 36.6–43.6%.

Some of the macro-porosity reduction methods, which need to be explored in future, include application of vibration/shaking, air expulsion, vacuum packing, and packing methods that takes advantage of parallel orientation of pellet cylindrical axes. Such methods, as a value addition stage, realize an overall increase in material handled per unit volume when applied to the pellets irrespective of their specific weights. Minimization of macro-porosity to the theoretical limit, as its value of granular materials cannot be brought down to zero based on packing theory, deserves further research.

The concept of porosity affects negatively on the quantity of useful material filled in a given space, thereby influences the transportation logistics of pellets. Simple techniques that increase the transport efficiency can be achieved by decreasing the porosity or increasing the bulk density by better packing/consolidation, as observed with tapped fill. Based on this research work, "minimization of macro-porosity" of wood pellets, towards the theoretical limit, should be viewed as an operation of biomass "densification," that can be achieved by simple techniques, such as vibration, air

Table 4
Students *t*-test for loose and tapped fill method for actual wood pellets volume.

Parameter	Fill method	Mean	STD	95% CI Mean	*t*-Value ($P > \|t\|$)
Macro-porosity (%)	Loose	40.95	2.51	40.27–41.63	10.90(< 0.0001)
	Tapped	35.50	2.73	34.76–36.23	
Bulk density (kg m^{-3})	Loose	669.6	28.50	661.90–677.30	−10.90(< 0.0001)
	Tapped	731.4	30.95	723.10–739.80	

Note: STD – Standard deviation; CI – Confidence interval; Equal variances – Pooled method; $df = 55$; $\alpha = 0.05$.

evacuation, vacuum application, and pellets layout and orientation in the future.

3.2.4. Hausner ratio and Carr's compressibility index

Actual wood pellets Hausner ratio varied from 1.05 to 1.14, with a mean of 1.09 ± 0.03, among the different fill volumes. A reduced Hausner ratio indicates a good flowability of granular material. Hausner ratios above 1.25 are considered to represent the threshold between "free flow" and "no flow" conditions (Podzeck, 1998; Schüssele and Bauer-Brandl, 2003). Hayes (1987) classified flow properties of food powders having fairly uniform size, shape, and increased bulk density based on Hausner ratio as: free flowing – 1.0–1.1, medium flowing – 1.1–1.25, difficult flowing – 1.25–1.4, and very difficult flowing – above 1.4. Based on this classification, the wood pellets can be classified as "freely flowing." Chevanan et al. (2008) measured the Hausner ratio of chopped biomass (screen size 12.5–50 mm) and reported values of 1.11–1.32 for switchgrass, 1.11–1.31 for wheat straw, and 1.06–1.24 for corn stover. When compared to these biomass, wood pellets have better flowability. These results also illustrate that the flowability of herbaceous lignocellulosic biomass can be improved by pelletization.

The Carr's compressibility index of actual wood pellets among studied fill volumes varied from 5.18% to 12.27%, with a mean of $8.44 \pm 2.30\%$. Material compressibility and flowablity are inversely related (Carr, 1965). Therefore, the flowability classification using Hausner ratio (Hayes, 1987) can be used to interpret the Carr's compressibility index values, as these values are interrelated (Eq. (10)). The Hausner ratio threshold value of 1.25 equates to Carr's compressibility index value of 20.0, similarly the free flowing range of Hausner ratio < 1.1 equates to Carr's compressibility index < 9.1. Original wood pellets mean and most of the Carr's compressibility index values at different fill volume were less than this limit of 9.1, thus classifying the wood pellets as "free flowing" material.

3.3. Comparison between porosities and specific densities by stereometric and pycnometer methods

Pycnometer based solids volume of the cylindrical wood pellets was $18,109 \pm 330$ mm^3, while the envelope volume based on stereometric measurement geometrical method was $22,110 \pm 682$ mm^3. This means the volume of the micro-pores of the sample (24.95 g) accessible to the gas under pressure used in pycnometer was 4001 mm^3 (160 mm^3 g^{-1}). The determined true density or solids density or specific weight of pellets was 1378 ± 9 kg m^{-3}, which was greater than the specific weight determined from the geometrical method (1128 ± 1 kg m^{-3}), since the solid volume was smaller than the envelope volume of the pellets. Thus, the consideration of micro-pores had reduced the effective pellet volume (solids volume) with respect to the envelope volume by $18.1 \pm 0.6\%$. Whereas, the true density had increased by $22.1 \pm 0.8\%$ with respect to the envelope density. This difference in densities was in the range of the reported difference of 26% between true and envelope densities based on studies of various food materials (Fasina, 2007a), with the variations can be attributed to the difference in material (species), nature (intact food grains versus mechanically extruded), and surface texture (presence of seed coat).

The porosity obtained from the relationship of bulk and true (pycnometer method) densities (Section 2.5), using the mean values (Table 4), for loose fill was 51.4% and that of tapped fill was 46.9%. These porosities had a difference of 10.5% (26% increase) and 11.4% (32% increase) from this study results (Table 4). This essentially indicates the micro-porosity contribution, from the respective loose and tapped fill geometric method porosities. Assuming similar trends, these results give an idea about the contribution of micro-pores in the wood pellet body and how they correlate to the measured envelope density (22% increase) with true density, and macro-porosity (loose fill 26% and tapped fill 32% increase) with total porosity. These results provide simple ways to well-informed estimates of pycnometer results from the developed geometrical method. The major limitation of the developed method would be that only the particulate materials with shapes resembling a regular geometry can be measured successfully.

4. Conclusions

The developed novel stereometric method of wood pellets macro-porosity measurement using geometrical principles is simple, inexpensive, handy, utilized common labware, and produced reproducible and accurate measurements. Actual wood pellets overall macro-porosity was determined as $41.0 \pm 2.5\%$ and $35.5 \pm 2.7\%$, and classified as "Class-3:Medium" and "Class-3&4:Medium to Low" for loose and tapped fills, respectively. Hausner ratio and Carr's compressibility index classify wood pellets as "freely flowing." Tapping significantly decreased the macro-porosity ($\approx$5%) and increased the bulk density (≈ 60 kg m^{-3}). Fill volume, mass, and bulk density correlate negatively with macro-porosity. As increased fill volumes ($\geqslant$1000 ml) not affecting measurements, the method is valid in scaled-up scenarios.

Acknowledgements

Financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC: CRDPJ 342219-06, UBC PG11R82830), and Wood Pellets Association of Canada (WPA: UBC PG11R42500) is highly appreciated and gratefully acknowledged.

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