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Variability of bulk density of distillers dried grains with solubles (DDGS) during gravity-driven discharge

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ABSTRACT

Loading railcars with consistent tonnage has immense cost implications for the shipping of distillers' dried grains with soluble (DDGS) product. Therefore, this study was designed to investigate the bulk density variability of DDGS during filling of railcar hoppers. An apparatus was developed similar to a spinning riffler sampler in order to simulate the filling of railcars at an ethanol plant. There was significant difference ($P < 0.05$) between the initial and final measures of bulk density and particle size as the hoppers were emptied in both mass and funnel flow patterns. Particle segregation that takes place during filling of hoppers contributed to the bulk density variation and was explained by particle size variation. This phenomenon is most likely the same throughout the industry and an appropriate sampling procedure should be adopted for measuring the bulk density of DDGS stored silos or transported in railcar hoppers.

1. Introduction

Distillers dried grains with solubles (DDGS) is the main co-product of fuel ethanol production from corn by the dry grind process. The marketability of DDGS has significant implications for the success of the ethanol industry. From its market value and the quantity produced, DDGS revenue can be as much as 20% of the total revenue from an ethanol plant. The fiber, oil and relatively high protein content in DDGS makes it suitable for animal feed (Rosentrater and Muthukumarappan, 2006). With the increase of fuel ethanol production, the production of DDGS has increased significantly in the last few years and reached 23 million metric tons in the 2008 marketing year (Renewable Fuel Association, 2010). Most of the DDGS is produced in the Mid-west region and is usually shipped primarily by rails or trucks to feedlots and ports throughout the US; hence handling and logistics are essential.

Maintaining a consistent bulk density of DDGS during handling and shipping is essential to minimizing shipping costs. Ileleji and Rosentrater (2008) pointed out the cost saving when DDGS of consistent bulk density is shipped. Ethanol plants have expressed concern about the inability to sequentially load railcars with consistent freight tonnage, even when the product was all from the same batch (Personal communication with The Anderson Clymers Ethanol in Indiana, 2007). Several researchers have highlighted the bulk density variability of DDGS. Rosentrater (2006) showed that the bulk density of DDGS produced at six ethanol plants in South Dakota ranged from 391 to 496 kg/m^3. Bhadra et al. (2009) found ranges of 490–590 kg/m^3 from five plants in South Dakota. In another study using DDGS from 69 sources in 2004 and 2005, it was found that the bulk density ranged from 365 to 561 kg/m^3 (US Grains Council, 2008). Some of these variations could be caused by differences in process conditions as pointed out by Kingsly et al. (2010). They showed that by varying the solubles content of a particular plant, the bulk density changed from 420.47 to 458.05 kg/m^3. However, all the above variations in bulk density referred to are the bulk density of DDGS sampled from the plant for physical and chemical property characterization. No study has been published investigating bulk density variation of DDGS during loading by gravity-driven discharge.

Of greatest concern to DDGS handlers is the inconsistency that exists when transporting DDGS from the same batch. The inability to achieve a consistent maximum tonnage increases the cost of shipping this product and underutilizes resources. Particle segregation takes place during handling operations of discharging from a hopper or silo (Ketterhager et al., 2007) and would similarly impact filling and emptying railcars transporting bulk DDGS. This could occur when different sized particles are lodged in segregated regions in a vessel causing the particle size distribution of a heterogeneous bulk to change with time during discharge (Shinohara et al., 1968; Fowler and Glastonbury, 1959). Shinohara et al. (1972) studied the size segregation of particles in filling a hopper and proposed the screen model for segregation of particles in filling a hopper. In this model, they suggested that when a bulk is poured and flows down the heap formed, small particles tend to be

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separated from the mixture by passing through the interspaces of large particles forming a flowing layer. These smaller particles drop into the gaps formed by the stationery layer of large particles under the flowing layer. A V-shaped zone in the hopper where the smaller particles are concentrated is formed. Shinohara and Miyata (1984) used this model to advance a mechanism of density segregation of particles in filling vessels. They deduced that denser particles behave like smaller particles in size segregation by settling near the feed line and forming a V-shaped narrow zone within the bed of lighter components.

Standish (1985) studied size segregation during filling and emptying of a hopper. He confirmed that during filling the hopper, smaller particles segregate in the center, large particles segregate towards the wall and the concentration of medium-size particles remain uniform throughout the hopper. He further determined in-bin segregation influences size segregation in the discharging of the material with concentration of small particles high in the discharge stream initially and low at the final stages. Salter et al. (2000) used a two-dimensional representation of a hopper to study the segregation of binary mixtures during filling; they expressed that segregation when forming a heap is influenced by different mechanisms within different regions of the heap. Bagster (1983) used mixtures of controlled size distribution and moisture content to investigate the effect on the segregation process, and concluded that the cohesivity of the material forming the heap influences the segregation process. The principles of these models have been validated using relatively homogeneous solids like glass beads, sand or similar materials but not thoroughly studied for heterogeneous bulk solids.

DDGS is a heterogeneous granular bulk solid (Ileleji et al., 2007) having particles of various sizes, morphological features and particle densities which are characteristic of the structural components of a corn kernel (germ, fiber, endosperm and tipcap). Shinohara (1979) studied the segregation of differently shaped particles in filling of storage vessels and found that angular particles behaves like smaller particles in size segregation being deposited near the feed point forming a V-shaped zone; therefore the heterogeneity of DDGS may exacerbate segregation during handling. Particle segregation during handling of DDGS was investigated by Ileleji et al. (2007) and Clementson et al. (2009), and found to occur during gravity-driven discharge. It is most likely that the bulk density variation observed during the filling of railcar hoppers might be caused by particle segregation. Therefore, the primary objective of this study was to investigate the bulk density variation of DDGS from a discharge vessel that simulated the filling of railcar hoppers, and determine the effect of particle segregation on the bulk density variation.

2. Methods

2.1. Materials and equipment

DDGS production involved the blending of condensed distillers soluble (CDS) and wet distillers grains (WDG), then drying the composite material using rotary drum dryers. Samples of DDGS for this study were prepared at a 416 million liters per year commercial fuel ethanol plant (The Andersons Clymers Ethanol plant in Clymers, Indiana) by varying the CDS and WDG composition. The process used incorporated two dryers in series where the total quantity input of CDS was split into the two dryers with the quantity of WDG remaining constant. Three distinct samples of DDGS produced by varying the CDS levels from the maximum amount routinely added at the plant to zero level (no CDS addition) were used in this study. The three CDS levels were: (i) about 7.39 percent volumetric basis (% v.b.), (ii) reduced to half of this amount, 3.69% v.b. and (iii) no CDS, 0% v.b. These samples were prepared in sequential order from 7.39%, 3.69% to 0% v.b. CDS respectively. Refer to Kingsly et al. (2010) for a detailed analysis of the physical and chemical variability in DDGS due to CDS levels.

To simulate the handling operation of filling and emptying of railcars at an ethanol plant; an equipment was assembled to sequentially sample bulk product being discharged from hoppers. The assembly (Fig. 1) consisted of a conveyor system (Model 2100-32A, C.W. Brabender Instrument Inc., NY), and a filling station similar to a spinning riffler sampler (Charlier and Goossens, 1971). The simulation was designed to accommodate mass (MF) or funnel (FF) flow, from hoppers mounted on a frame which empties into sixteen (16) cups that sit on a rotating table (turn-table) driven by an electric right angle gear motor (Model 1XFY8, Dayton, Burton, MI). The advantages and disadvantages of each flow mode are well documented (Marinelli and Carson, 2001) along with the impact of hopper design, material characteristics and operating conditions (Carson et al., 2008). Each cup was 550 cm^3 in volume and holds about 250 g of DDGS on average. The hoppers were composed of perplex glass cylinder of 30.5 cm diameter that fit into aluminum cones of half angles 36° and 65° for the mass flow and funnel flow hoppers, respectively and discharge diameter of 5.1 cm.

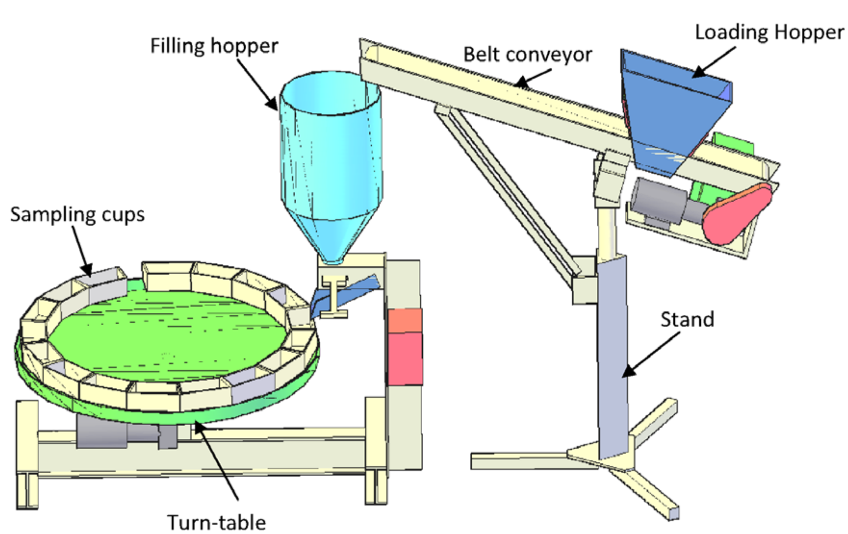

Fig. 1. DDGS loading simulation assembly consisting of the conveyor system and loading station.

2.2. Loading simulation

About 0.011 m^3 of DDGS from the tote bags were thoroughly mixed in a bucket, and then gradually loaded onto the belt conveyor using a scoop while ensuring that the conveyor was not overloaded; this reflected the random loading of the conveyor at a DDGS facility. The belt conveyor had speed of about 6.41 cm/s; it transported the DDGS which was freely discharged to fill the hopper. The hopper had a discharge control stopper to control the flow of material from the hopper. After the hopper was filled with material, the belt conveyor was stopped. The turn-table was started; it rotated the sampling cups below the hopper's discharge outlet at about 0.1 m/s. DDGS material was discharged by gravity into the sampling cups in sequence from cup No. 1 to 16 by opening and closing the hopper discharge stopper to ensure the sampling cups are filled, simulating the loading of railcar hoppers sequentially. After all the cups were filled with DDGS, the turn-table's motor was stopped, and the DDGS from each cup was placed

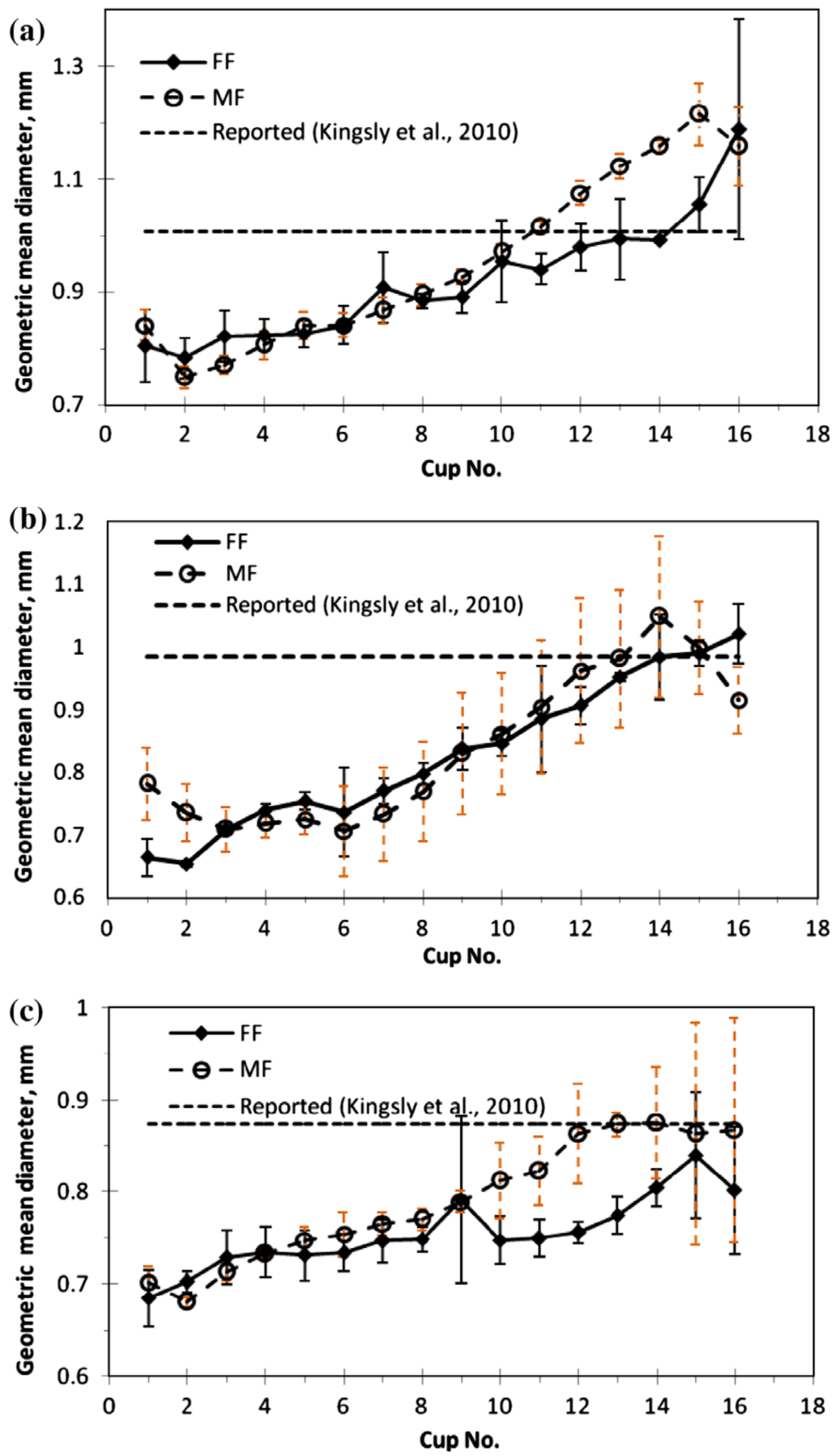

Fig. 2. Particle size variation of DDGS from (a) 7.39% v.b., (b) 3.69% v.b. and (c) 0% v.b. CDS samples captured in each cup using funnel (FF) and mass (MF) flow hoppers.

in Ziploc© bags and labeled sequentially in the order they were filled. Bulk density measurement and particle size analysis was done for samples collected in each cup. The experiments were conducted in triplicates for each sample.

2.3. Bulk density measurement and particle size analysis

The bulk density of DDGS samples from the cups was measured using a Seedburo grain density equipment (Seedburo Equipment Co., Des Plaines IL), which consists of a brass hopper with a valve at its exit, mounted in a tripod that opens into a measuring cup. The hopper was centered over the measuring cup (160 cm^3) with its valve closed and DDGS was poured into the hopper. The hopper valve was opened quickly and DDGS was allowed to flow freely into the measuring cup, care was taken to ensure there was consistency in the equipment setup (Clementson et al., 2010). After the cup was filled, the excess material was leveled off with gentle zig–zag strokes using a standard Seedburo striking stick. The bulk density of DDGS was calculated from the mass and volume of DDGS using the following expression:

$$\text{Bulk density},\ \rho = \frac{\text{mass of DDGS in measuring cup, m}}{\text{volume of measuring cup,} \nu} \tag{1}$$

The samples were split using a Boerner divider (Seedburo Equipment Co., Chicago, IL) to obtain sub-samples of about 100 g from each cup for particle size distribution (PSD) analysis. The PSD analysis was conducted using the standard procedure outlined in the ANSI/ASAE S319.3 standard (ASAE Standards, 2005). Sieves

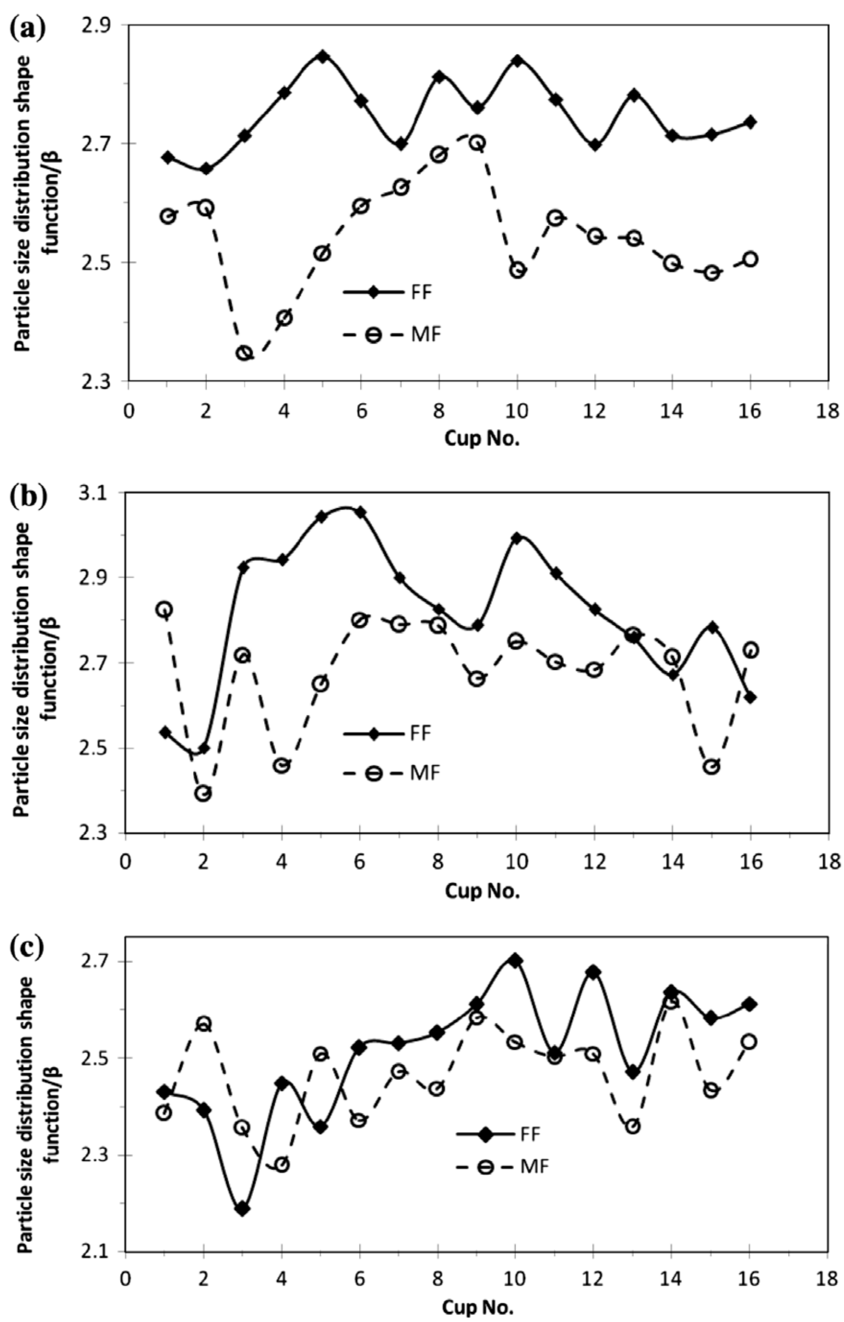

Fig. 3. Particle size distribution shape function of DDGS from (a) 7.39% v.b., (b) 3.69% v.b. and (c) 0% v.b. CDS samples captured in each cup using funnel (FF) and mass (MF) flow hoppers.

ranging from US sieve No. 4 (sieve opening 4.75 mm) to sieve No. 270 (sieve opening 0.053 mm) were stacked in increasing number from top to bottom in a Ro-Tap Shaker (Model RX-29, W.S. Tyler Inc., Mentor, OH, USA.). A sample of about 100 g was placed on the top sieve and the shaker was operated for about 10 min after which the weight of DDGS on each sieve was measured. The geometric mean diameter (d_{gw}) and the geometric standard deviation (S_{gw}) were calculated according to the procedure mentioned in the standard. Additionally, the Rosin–Rammler distribution function was applied to each cup's particle distribution to compare the distribution shape of the flow patterns. The Rosin–Rammler system has been used for biological materials (Perfect et al., 1998) and is considered accurate for granular heterogeneous particles (Allaire and Parent, 2003). The Rosin–Rammler function was linearized as:

$$\ln\left[\ln\left(\frac{1}{1-F(x)}\right)\right] = \beta \ln x - \beta \ln \alpha \quad (2)$$

where β is the slope and gives the shape/spread of the particle size distribution, $\beta \ln \alpha$ is the intercept with α being the mean particle size, and $F(x)$ is the cumulative distribution of particle size x.

Statistical analysis was conducted on the geometric mean diameter of each cup SAS v9.1 (SAS Institute, Cary, NC) PROC GLM analysis of variance (ANOVA) procedure was used to determine whether statistical differences exist between the geometric mean particles, and correlated with the distribution shape function from the Rosin–Rammler system to evaluate particle segregation during gravity-driven discharge. Additionally, PROC GLM analysis of variance procedure was used to compare the geometric mean particle size and bulk density obtained from each cup for each flow pattern. PROC TTEST (SAS v9.1, SAS Institute, Cary, NC) was used to determine if the geometric mean particle size or bulk density obtained from in each cup for both flow patterns are significantly different ($P < 0.05$).

3. Results and discussion

Fig. 2 show a trend of increasing geometric mean particle size as the hoppers were emptied sequentially into cups No. 1 to 16 for all three samples. There were also significant differences ($P < 0.05$) in geometric mean particle size of the cups within each of the three samples. These trends indicate that the particles exiting the hoppers were segregated. Fig. 3 illustrates the randomness of the particle size distribution which characterizes the randomness of the discharge process. However, most notable is that the distribution shape functions for funnel flow tests were generally higher than those for mass flow indicating that the particle size distribution for funnel flow were narrower than for mass flow (Bitra et al., 2009). This is because of the distinct difference of the flow patterns between funnel and mass flow and the segregation that took place on filling the hoppers. On filling the hoppers, smaller particles segregates in the center and large particles towards the hopper wall, in funnel flow the center empties first then the particles close to the wall's surface; hence the particles are discharged primarily according to particle size. Whilst for mass flow which employs the first in first out principle, particles from the center and surface would be discharged together hence having a wider particle size distribution. These results corroborate the findings of Shinohara et al. (2001) and Standish (1985) who pointed out that during filling of a hopper, smaller particles accumulate in the center while large particles a towards the wall, and in-bin segregation influences size segregation in the discharging of the material.

For the 7.39% v.b. CDS sample, the geometric mean particle size of DDGS in cup No. 1 to 16 ranged from 0.78 to 1.19 mm for funnel flow and 0.75 to 1.16 mm for mass flow; for the 3.69% v.b. CDS sample, the particle size ranged from 0.65 to 1.02 mm for funnel flow and 0.71 to 1.05 mm for mass flow; for the 0% v.b. CDS sample, the particle size ranged from 0.69 to 0.84 mm for funnel flow and 0.68 to 0.88 mm for mass flow (Table 1). The particle sizes reported for the composite bulk of samples 7.39%, 3.69% and 0% v.b. CDS were 1.01, 0.99 and 0.87 mm, respectively (Kingsly et al., 2010). The range of geometric mean particle size of these tests were within the range reported by Clementson et al. (2009) and higher than the values reported by Liu (2008). The geometric mean diameter of all the samples for both mass and funnel flow were almost similar from cup No. 1 to 10; this is an indication of segregation regions that occurred during filling the hoppers. On filling the hoppers initially there is complete mixing of the particles until a sufficient particle bed exists to aid in the segregation (Shinohara et al., 1972); on discharge, mixed particles exit until the segregated region is reach which in this case would be about the 10th cup.

Fig. 4 shows the bulk density had a decreasing pattern for both the funnel flow (FF) and mass flow (MF) hoppers as the hopper emptying process transpired over time as the cups were filled sequentially. The decrease seems similar for both flow patterns

Table 1
Comparisons of geometric mean particle size obtained from each cup by funnel and mass flow for each sample.

	CDS								
	7.39% v.b.			3.69% v.b.			0% v.b.		
Cup No.	Funnel flow[1] (mm)	Mass flow[1] (mm)	*t*Test[2]	Funnel flow (mm)	Mass flow (mm)	*t*Test	Funnel flow (mm)	Mass flow (mm)	*t*Test
1	0.80 c,d	0.84 g,h,i	0.418	0.66 g	0.78 b,c,d,e	0.084	0.69 c	0.70 c	0.443
2	0.78 d	0.75 J	0.219	0.65 g	0.74 d,e	0.098	0.70 b,c	0.68 c	0.036
3	0.82 c,d	0.77 i,j	0.136	0.71 f,g	0.71 e	0.990	0.73 b,c	0.71 b,c	0.419
4	0.82 c,d	0.81 h,i,j	0.480	0.74 e,f,g	0.72 e	0.309	0.74 a,b,c	0.73 a,b,c	0.925
5	0.83 c,d	0.84 g,h,i	0.483	0.75 d,e,f,g	0.73 e	0.219	0.73 b,c	0.75 a,b,c	0.402
6	0.84 c,d	0.84 g,h,i	0.995	0.74 e,f,g	0.71 e	0.678	0.73 a,b,c	0.75 a,b,c	0.338
7	0.91 b,c,d	0.87 f,g,h	0.341	0.77 d,e,f,g	0.73 e	0.556	0.75 a,b,c	0.77 a,b,c	0.288
8	0.88 b,c,d	0.90 e,f,g	0.459	0.80 c,d,e,f,g	0.77 c,d,e	0.667	0.75 a,b,c	0.77 a,b,c	0.104
9	0.89 b,c,d	0.93 e,f	0.111	0.84 b,c,d,e,f	0.83 a,b,c,d,e	0.926	0.79 a,b,c	0.79 a,b,c	0.971
10	0.95 b,c,d	0.97 d,e	0.795	0.85 b,c,d,e,f	0.86 a,b,c.d.e	0.854	0.75 a,b,c	0.81 a,b,c	0.086
11	0.94 b,c,d	1.02 c,d	0.010	0.89 a,b,c,d,e	0.90 a,b,c,d,e	0.847	0.75 a,b,c	0.82 a,bc	0.039
12	0.98 a,b,c,d	1.08 b,c	0.023	0.91 a,b,c,d	0.96 a,b,c,d	0.576	0.76 a,b,c	0.86 a,b	0.028
13	0.99 a,b,c	1.12 b	0.041	0.95 a,b,c	0.98 a,b,c	0.749	0.78 a,b,c	0.87 a	0.002
14	0.99 a,b,c,d	1.16 a,b	0.006	0.98 a,b	1.05 a	0.574	0.81 a,b	0.88 a	0.132
15	1.06 a,b	1.22 a	0.019	0.99 a,b	1.00 a,b	0.883	0.84 a	0.86 a,b	0.787
16	1.19 a	1.16 a,b	0.814	1.02 a	0.92 a,b,c,d,e	0.110	0.80 a,b	0.87 a,b	0.461
p-Value[3]	<0.0001	<0.0001		<0.0001	<0.0001		0.0004	<0.0001	

[1] Means with the same lower case letter are not significantly different at 0.05 probability level for the same sample and flow pattern.
[2] Probability that the mean values are equal for mass and funnel flow patterns.
[3] Probability the means of all the cups are equal for the same flow pattern.

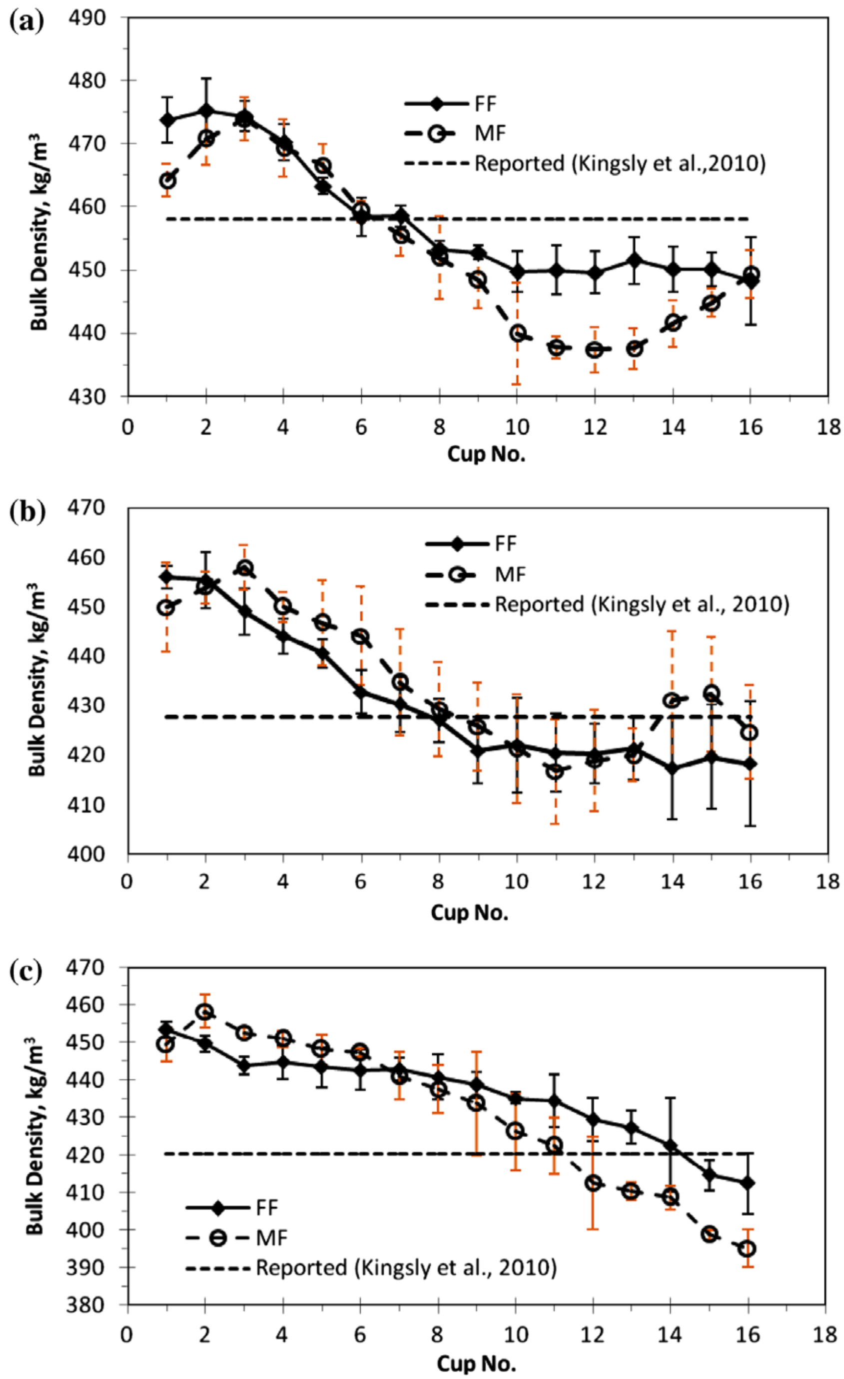

Fig. 4. Bulk density of DDGS during filling of each cup for (a) 7.39% v.b., (b) 3.69% v.b. and 0% v.b. CDS samples using both funnel flow (FF) and mass flow (MF) hoppers.

from cup No. 1 to about cup No. 10 for all the samples then decrease at different rates through to cup No. 16. As pointed out previously, this may be due to the distinctive segregated region after filling particles that is particles not being segregated initially at filling.

The bulk density of the 7.39% v.b. CDS samples ranged from 475.31 to 448.27 kg/m^3 for funnel flow, and 474.06 to 437.38 kg/m^3 for mass flow; for the 3.69% v.b. CDS sample, bulk density ranged from 456.04 to 417.33 kg/m^3 for funnel flow and 457.96 to 416.77 kg/m^3 for mass flow; for the 0% v.b. CDS sample, bulk density ranged from 453.42 to 412.44 kg/m^3 for funnel flow and 458.29 to 395.23 kg/m^3 for mass flow. The reported bulk density of the samples determined using composite samples collected in the totes were 458.05, 427.7 and 420.47 kg/m^3 for the 7.39%, 3.69% and 0% v.b. CDS samples respectively (Kingsly et al. 2010). There was no distinctive trend for the difference in particle size and bulk density for the flow patterns, although some differences were significant for the 7.39% and 0% v.b. CDS samples, and the difference for the 3.69% v.b. CDS sample was significant for both particle size and bulk density (Table 1 and 2).

The data from this study validate the hypothesis that there is bulk density variation as DDGS is loaded and emptied at ethanol plants. Bulk density variation was shown to be primarily caused by particle segregation that takes place while filling the hopper and during discharge either in mass flow or funnel flow patterns. Density segregation, the segregation of particles in the bulk based on density difference (Tanaka, 1971), also influenced the density variation experienced. During flow in filling the hopper, the denser

Table 2
Comparisons of bulk density obtained from each cup by funnel and mass flow for each sample.

	CDS								
	7.39% v.b.			3.69% v.b.			0% v.b.		
Cup No.	Funnel flow[1] (kg/m^3)	Mass flow[1] (kg/m^3)	*t*Test[2]	Funnel flow (kg/m^3)	Mass flow (kg/m^3)	*t*Test	Funnel flow (kg/m^3)	Mass flow (kg/m^3)	*t*Test
1	473.88 a	464.23 b,c,d	0.020	456.04 a	449.83 a,b,c	0.313	453.42 a	449.35 a,b	0.229
2	475.31 a	470.77 a,b	0.288	455.40 a	453.88 a,b	0.705	449.58 a,b	458.29 a	0.035
3	474.44 a	474.06 a	0.883	449.02 a	457.96 a	0.075	443.88 a,b,c,d	452.58 a,b	0.005
4	470.35 a,b	469.38 a,b	0.768	444.04 a,b	449.94 a,b,c	0.098	444.83 a,b,c	450.90 a,b	0.103
5	463.31 a,b,c	466.63 a,b,c	0.192	440.63 a,b,c	446.71 a,b,c,d	0.306	443.44 a,b,c,d	448.10 a,b	0.294
6	458.49 b,c,d	459.33 c,d,e	0.688	432.77 b,c,d	444.13 a,b,c,d,e	0.146	442.65 a,b,c,d	447.21 a,b	0.216
7	458.63 b,c,d	455.50 d,e,f	0.206	430.27 b,c,d	434.67 a,b,c,d,e	0.563	442.85 a,b,c,d	441.06 a,b,c	0.671
8	453.31 c,d	451.98 e,f,g	0.749	427.06 c,d	429.29 b,c,d,e	0.730	440.77 a,b,c,d	437.58 b,c	0.561
9	452.81 c,d	449.48 f,g,h,i	0.163	420.98 d	425.75 b,c,d,e	0.502	438.67 a,b,c,d,e	433.69 b,c	0.575
10	449.73 d	439.94 i,j	0.121	422.06 d	421.35 d,e	0.937	435.13 b,c,d,e	426.17 c,d	0.213
11	450.00 d	437.77 J	0.008	420.48 d	416.77 e	0.651	434.42 b,c,d,e	422.44 c,d	0.114
12	449.63 d	437.38 J	0.012	420.29 d	418.92 d,e	0.849	429.43 c,d,e,f	422.44 d,e	0.100
13	451.56 c,d	437.58 J	0.008	421.40 d	420.04 d,e	0.792	427.35 d,e,f,g	410.44 d,e	0.004
14	450.17 d	441.54 h,i,j	0.045	417.33 d	431.08 a,b,c,d,e	0.241	422.73 e,f,g	408.79 d,e	0.136
15	450.10 d	444.83 g,h,i,j	0.057	419.71 d	432.35 a,b,c,d,e	0.232	414.63 f,g	398.75 e	0.003
16	448.27 d	449.40 f,g,h	0.816	418.25 d	424.65 c,d,e	0.520	412.44 g	395.23 e	0.034
p-Value[3]	<0.0001	<0.0001		<0.0001	<0.0001		<0.0001	<0.0001	

[1] Means with the same lower case letter are not significantly different at 0.05 probability level for the same sample and flow pattern.
[2] Probability that the mean values are equal for mass and funnel flow patterns.
[3] Probability the means of all the cups are equal for the same flow pattern.

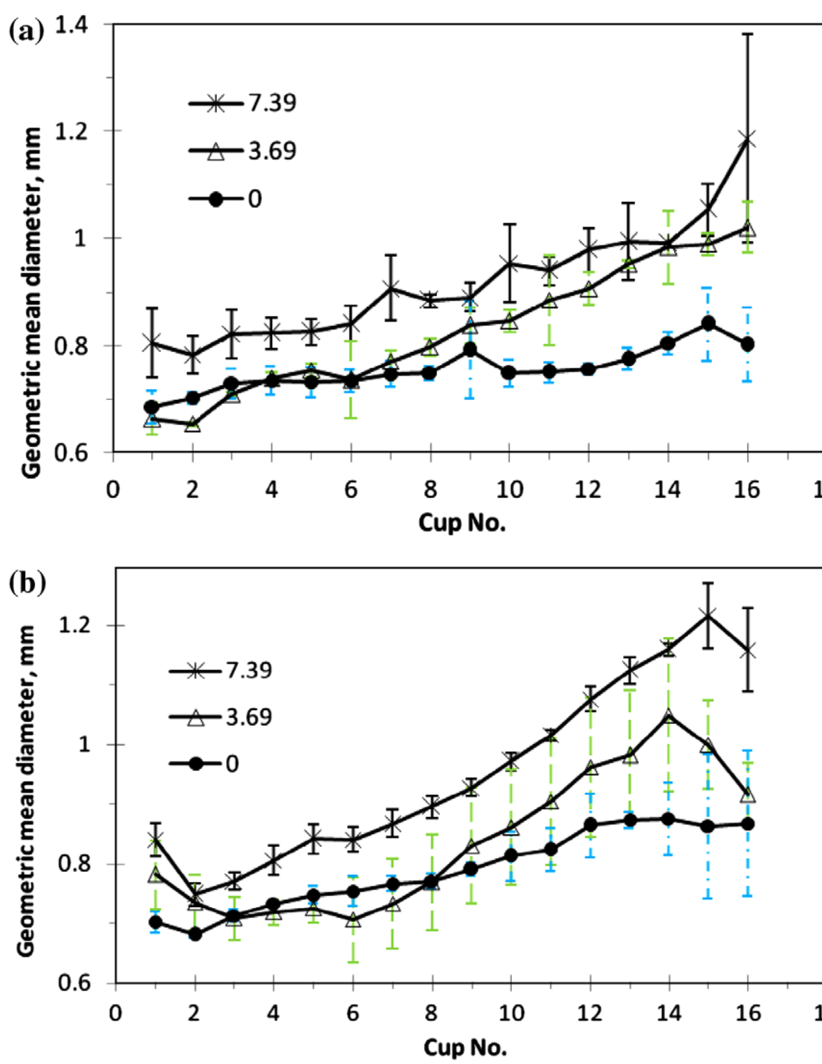

Fig. 5. Particle size variation of DDGS for all three samples (% v.b. CDS) captured in each cup using (a) funnel flow and (b) mass flow hopper.

Table 3
Comparison of the geometric mean particle size obtained for each sample using the same flow pattern.

	Cup No.							
	Funnel flow				Mass flow			
	7.39%[3] (mm)	3.69% (mm)	0% (mm)	*p*-Value[1]	7.39% (mm)	3.69% (mm)	0% (mm)	*p*-Value
1	0.80 a[2]	0.66 a,b	0.69 b	0.036	0.84 a	0.78 a,b	0.70 b	0.013
2	0.78 a	0.65 b	0.70 b	0.005	0.79	0.74	0.68	0.059
3	0.82 a	0.71 a,b	0.73 b	0.025	0.77 a	0.71 b	0.71 a,b	0.030
4	0.82 a	0.74 b	0.74 b	0.016	0.81 a	0.72 b	0.73 b	0.003
5	0.83 a	0.75 b	0.73 b	0.011	0.84 a	0.73 b	0.75 b	0.001
6	0.84	0.74	0.73	0.050	0.84 a	0.71 b	0.75 a,b	0.028
7	0.91 a	0.77 b	0.75 b	0.013	0.87 a	0.73 b	0.77 a,b	0.027
8	0.88 a	0.80 b	0.79 c	<0.001	0.90 a	0.77 b	0.77 b	0.018
9	0.89	0.84	0.79	0.240	0.93	0.83	0.79	0.061
10	0.95 a	0.85 a,b	0.75 b	0.015	0.97 a	0.86 a,b	0.81 b	0.048
11	0.94 a	0.89 a	0.75 b	0.008	1.02 a	0.90 a,b	0.82 b	0.030
12	0.98 a	0.91 a	0.76 b	0.001	1.08 a	0.96 a,b	0.86 b	0.037
13	0.99 a	0.95 a	0.78 b	0.005	1.12 a	0.98 a,b	0.87 b	0.009
14	0.99 a	0.98 a,b	0.81 b	0.031	1.16 a	1.05 a,b	0.88 b	0.015
15	1.06 a	0.99 a,b	0.84 b	0.011	1.22 a	1.00 a,b	0.86 b	0.007
16	1.19 a	1.02 a,b	0.80 b	0.042	1.16 a	0.92 b	0.87 b	0.013

[1] Probability the means of the samples using the same flow pattern are equal for the same cup.
[2] Means of the same cup number with the same lower case letter are not significantly different at 0.05 probability level for the same flow pattern.
[3] Volumetric basis (v.b.) CDS level.

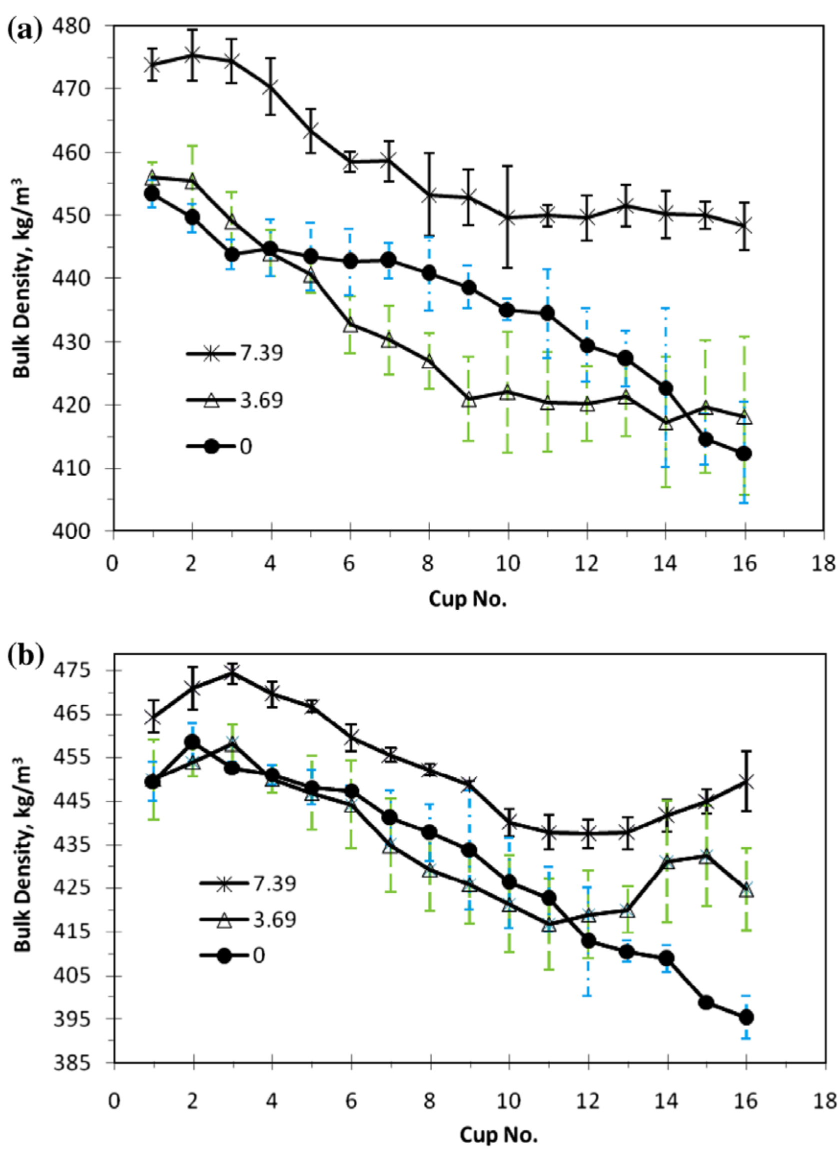

Fig. 6. Bulk density of DDGS for all three samples (% v.b. CDS) using (a) funnel flow and (b) mass flow hopper.

Table 4
Comparison of the bulk density obtained for each sample using the same flow pattern.

	Cup No.							
	Funnel flow				Mass flow			
	7.39%[3] (kg/m^3)	3.69% (kg/m^3)	0% (kg/m^3)	*p*-Value[1]	7.39% (kg/m^3)	3.69% (kg/m^3)	0% (kg/m^3)	*p*-Value
1	473.88 a[2]	456.04 b	453.42 b	<0.001	464.23	449.83	449.35	0.050
2	475.31 a	455.40 b	449.58 b	<0.001	470.77 a	453.88 b	458.29 b	0.007
3	474.44 a	449.02 b	443.88 b	<0.001	474.06 a	457.96 b	452.58 b	<0.001
4	470.35 a	444.04 b	444.83 b	<0.001	469.38 a	449.94 b	450.90 b	<0.001
5	463.31 a	440.63 b	443.44 b	<0.001	466.63 a	446.71 b	448.10 b	0.007
6	458.49 a	432.77 b	442.65 b	<0.001	459.33 a	444.13 b	447.21 a,b	0.047
7	458.63 a	430.27 b	442.85 c	<0.001	455.50 a	434.67 b	441.06 a,b	0.031
8	453.31 a	427.06 a,b	440.77 b	0.004	451.98 a	429.29 b	437.58 a,b	0.016
9	452.81 a	420.98 b	438.67 c	<0.001	449.48	425.75	433.69	0.067
10	449.73 a	422.06 a,b	435.13 b	0.010	439.94	421.35	426.17	0.099
11	450.00 a	420.48 b	434.42 b	0.003	437.77 a	416.77 a,b	422.44 b	0.040
12	449.63 a	420.29 b	429.43 b	0.001	437.38 a	418.92 a,b	422.44 b	0.045
13	451.56 a	421.40 b	427.35 b	<0.001	437.58 a	420.04 b	410.44 b	<0.001
14	450.17 a	417.33 b	422.73 b	0.012	441.54 a	431.08 a	408.79 b	0.009
15	450.10 a	419.71 b	414.63 b	0.001	444.83 a	432.35 a	398.75 b	<0.001
16	448.27 a	418.25 b	412.44 b	0.006	449.40 a	424.65 b	395.23 c	<0.001

[1] Probability the means of the samples using the same flow pattern are equal for the same cup.
[2] Means of the same cup number with the same lower case letter are not significantly different at 0.05 probability level for the same flow pattern.
[3] Volumetric basis (v.b.) CDS level.

components penetrates through dynamically formed voids to the bottom layer close to the feed point by pushing away lighter particles (Shinohara et al., 2002; Dolgunin et al., 1998) or due to the impact of particles with the heap (Lawrence and Beddow, 1968).

After filling; the finer, smaller and denser particles were concentrated at the center of the filling hopper and the larger, coarser and less dense particles were concentrated at the sides of the hopper. In funnel flow discharge from the hopper, the finer and denser particles at the center discharged first resulting in a higher density initially, and the coarser and less dense particles located on the hopper wall last resulting in a lower density. The trend in bulk density variation observed for mass flow patterns was not distinctly different from those of funnel flow, this could be because the scale of the experiments conducted was not adequate to overcome the particle turbulence caused by gravity suction at the hopper discharge opening (Shinohara et al., 1973) or the dynamic arch form by the gravity flow of particles from an hopper (Shinohara et al., 1968) which causes pulsation of solids on discharge, may not have promoted a truly mass flow pattern (Nedderman et al., 1983; Shinohara and Tanaka, 1975; Carleton, 1972). Additionally, in loading railcars the distance down the slope would be larger than that obtained from the test hoppers hence the degree of segregation would be greater (Salter et al., 2000; Shinohara and Golman, 2002). However these results show that particle segregation would occur when railcars are loaded with DDGS and explain the density variation that occurs.

Further evaluation of the data shows that the 7.39% v.b. CDS sample had a larger geometric mean diameter throughout the test than the 3.69% v.b. CDS and 0% v.b. CDS samples for both funnel and mass flows (Fig. 5; Table 3). Also the bulk density of the 7.39% v.b. CDS sample was higher than for the 3.69% v.b. CDS and 0% v.b. CDS samples throughout the test for both funnel and mass flows (Fig. 6; Table 4). The increased CDS level in the 7.39% v.b. CDS sample provided more binder for the agglomeration of the particles hence forming larger, denser granules (Kingsly et al., 2010). This emphasizes the importance of manufacture process to the physical properties and should be considered when examining physical phenomenon of materials.

4. Conclusion

This study evaluated the bulk density variation of DDGS when filling and emptying hoppers simulating the loading of railcars at an ethanol plant. It shows that there was bulk density and particle size variation as the hoppers were emptied. Segregation that takes place while filling the hoppers is amplified during discharge causing bulk density variation. The results from this study when expanded to practical situation, justifies the inconsistency of bulk density obtained from loaded railcars and that an appropriate sampling procedure should be adopted for measuring the bulk density of DDGS stored silos or transported in railcar hoppers.

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