World Applied Sciences Journal 13 (9): 1996-2004, 2011
ISSN 1818-4952

Experimental Study of the Repose Angles of Corn Seeds in Rotating Drums

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Abstract: The processing of particles in rotating drums is heavily influenced by the type of flow regimes within the drums during rotation. The type of flow regimes will, in turn, affects the uniformity and ultimately the quality of particle processing. Slumping and rolling motion are most important mode of motion of granular materials in rotating drums for their frequently use in various processes. In the present study, small scales of rotating drums were used to investigate the lower, upper and dynamic angle of repose (AR) of corn seeds (CS) in slumping and rolling motions. The drum diameters were 150 mm, 180 mm and 300 mm. The effect of (a) filling degree, (b) drum diameter and (c) the ratio of particles to drum diameter (d/D) on the angles of repose of corn seeds within rotating drums was investigated in this study. All of these factors had significant effect on the AR of CS. A correlation between the lower and upper AR of CS is obtained. The results are applicable in practice for example in design of various processing equipment and in mathematical modeling of the slumping and rolling motion and their transition.

Key words: Corn seeds · Rotating drum · Angle of repose · Slumping motion · Rolling motion · Size ratio

INTRODUCTION

Rotating drums are widely used in the agricultural and food industries as mixers, dryers and reactors [1]. They are made of a long cylindrical shell that is rotated. The shell is usually slightly inclined to the horizontal to induce solids flow from one end of the drum to the other [2].

The attraction of the rotating drum lies in its simplicity and inherent flexibility in design and the broad range of material characteristics that can be tolerated along the length of one continuous unit. The principal modes of operation of rotating drums in solids processing are characterized in terms of the cross sectional behavior of the bed, which progresses through six characteristic patterns as rotation speed, characterized by the Froude Number increases. A characteristic criterion for the motion of solids in rotary drums is the Froude number (Fr) as the ratio of centrifugal force to gravity. The centrifugal force is related to the inner radius of the cylinder so that this criterion is also named the peripheral Froude number and calculated from [3]:

$$\mathrm{Fr} = \frac{\mathrm{R}.\omega^2}{\mathrm{g}} \quad (1)$$

Where R is inner radius of rotating drum (m), ω is angular rotation speed (s^{-1}) and g is gravitational acceleration ($m\ s^{-2}$).

The motion behavior of granular solid in the transverse plane of a rotary drum (Figure 1) depends on the operating conditions such as rotational speed and filling degree of drum [1,4-6]. These patterns are shown in Figure 1. A detailed description of the transverse flow regimes is presented by Mellmann [3].

The filling degree (f) as the portion of the cylinder cross-section occupied by the bed is determined by the filling angle (ϵ) as follows [3]:

$$\mathrm{f} = \frac{1}{\pi}(\varepsilon\text{-Sin}\varepsilon\text{Cos}\varepsilon) \quad (2)$$

The filling angle ϵ corresponds to the half bed angle of the circular segment occupied with solids.

Although six modes of motion have been observed in rotating drums, industrial-scale drums are often operated in the rolling or slumping mode [6-9].

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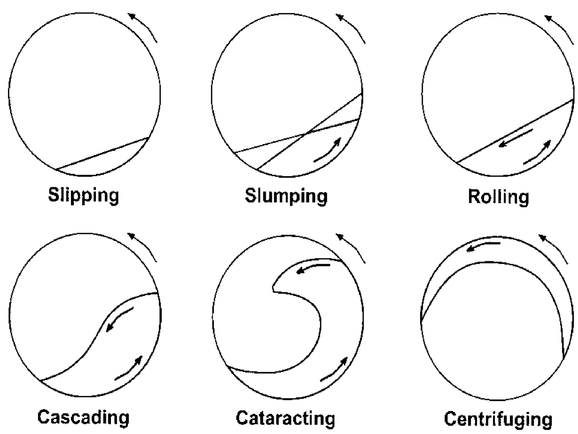

Fig. 1: Types of granular material motion in rotary drums [9].

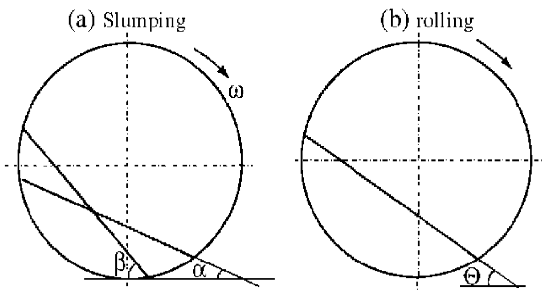

Fig. 2: The slumping motion and the rolling motion [7].

Among the various modes of the granular motion in rotating drums, the slumping mode and the rolling mode have been frequently investigated due to their importance in industrial operations. The important parameters describing the slumping and rolling modes are the angles of repose of the granular material [7]. The angles of repose are important to design the handling systems, storage constructions, mixtures, dryers and milling systems [10]. The angle of repose (AR) strongly depends on material properties such as sliding and rolling frictions, density of grains and grain characteristics such as size and shapes [11]. The AR is a good indicator of the flow ability of uncompacted materials [12,13].

With very smooth drum wall, slipping motion may be occurred (Figure 1). Since no mixing occurs in slipping motion, it is undesired in practice. With higher increase in rotation speed and/or wall friction coefficient the slumping motion can be observed. This mode is characterized by the upper and lower AR, as shown in Figure 2(a). At this case, the granular bed is lifted as a rigid body by the rotating drum wall until it reaches the upper AR, β, at which seeds on the bed surface begin to slide down in the form of an avalanche (Figure 2(a)). During the avalanching, the slope of the bed surface is decreased to the lower AR, α. The bed is then lifted again to the angle β and a new avalanche starts [14]. The slumping frequency is dependent on rotational speed, particle size and drum diameter [15]. As the rotational speed increases a flowing transition to rolling takes place where the slope of the bed surface remains approximately constant (the dynamic AR, θ), as shown in Figure 2(b) 17].

The critical Froude number that is found to be proportional to $(\beta\text{-}\alpha)^2$, is needed for develop of mathematical models to predict the transition from the slumping mode to the rolling mode [3, 16]. To calculate the Froude number, both the lower AR and upper AR that have been treated as two independent variables in literature have to be measured. It is almost impossible to measure them with an error lower than ±0.5°. Due to the measuring errors, the value of $(\beta\text{-}\alpha)^2$ scatters in a wide range and the calculated critical Froude number is affected significantly. This is highly disadvantageous for the models to be used in practice [7].

Liu *et al.* [7, 8], Mellmann [3] and Spurling *et al.* [10] concluded that the average upper and lower AR for the slumping mode is close to the dynamic AR for the rolling mode, i.e.:

$$\theta = \frac{\alpha + \beta}{2} \tag{3}$$

In recent years, Effect of some operating parameters such as rotation speed, drum diameter, feeling degree on upper and lower AR of engineering materials have been studied by several investigators [14]. It was found very little published information on determining angles of repose for agricultural products in the rotating drums. Compared to the much work on investigating the dynamic AR, there have been only a few experimental studies on the lower AR and upper AR.

Considering the importance of the lower and upper angles in the mathematical modeling, the objectives of this study were to investigate (I) The effect of filling degree, drum diameter and size ratio (ratio of particle to drum diameter) on lower, upper and dynamic AR and (II) if the lower and upper AR are independent or dependent on each other.

The size ratio (d/D) is a dimensionless geometric variable, which is frequently used to describe the granular motion in rotating drums [3, 17]. It is therefore interesting to know how this variable influences the lower, upper and dynamic AR of corn seeds.

Fig. 3: Apparatus for measuring the angles of repose

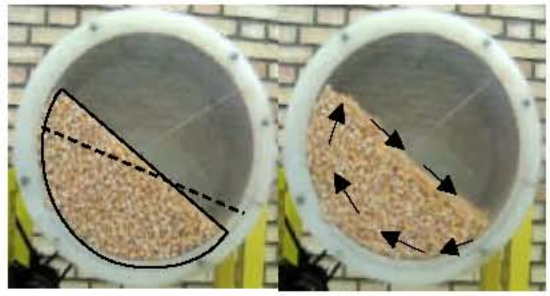

Fig. 4: Slumping (left) and Rolling (right) motion of CS in rotating drum (D=300mm, f=0.4)

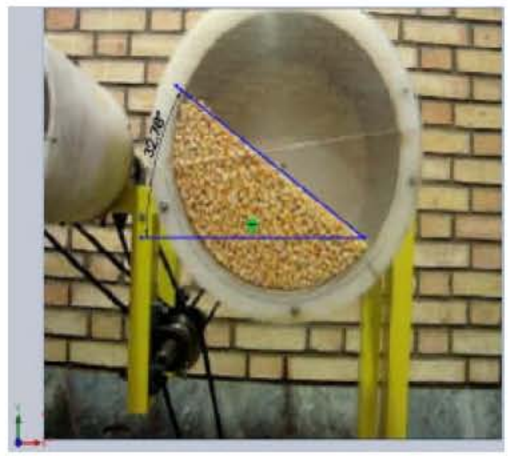

Fig. 5: Measurement of angles of repose of CS in Solid works 2008 software

MATERIALS AND METHODS

Preparation of Corn Seeds: Corn seeds (CS) were obtained from a local market in Tehran, Iran. The seeds were cleaned manually to remove all foreign material and broken seeds. The physical dimensions of the CS were determined by taking 100 seeds randomly and measuring the seeds linear dimensions (length, width and thickness) using a micrometer reading to 0.05 mm. For each seed, the geometric mean diameter, sphericity, volume and surface area were determined using the equations reported by Mohsenin [18]. The bulk density, true density and 1000-seed mass were determined according to the methods proposed by Kingsly *et al.* [19].

Experimental Set-up: The experimental apparatus used in present study is shown in Figure 3. The set-up consists of three horizontal drum. For visual observation, front of drums is fixed with a transparent plate. Because of frequently use of galvanized iron in postharvest equipment, this surface was selected and used in the inner wall of the drums. The length of drums was 200 mm and inner diameters of drums were 150 mm, 180 mm and 300 mm. The drums were rotated by a 0.75 kW electrical geared motor. With an inverter (Lenze 8300, Germany), adjustable rotation speeds from 0.5 to up to 100 rpm were attainable. The granular motion was recorded as video films with a digital video camera (Sony DSC-W120 7.3 Mega pixel, Japan). The camera as shown in Figure 3 was placed in such a way that the centre of the camera lens points exactly to the centre of the rotating drum [2]. Then the recorded films transported to a PC.

Experimental Procedure: For measuring the angles of repose, the drums partly filled with CS. Values of 0.2, 0.3 and 0.4 for the degree of fill were selected for this study. Filling degrees lower than 0.2 are unfavorable for the visual observation of the avalanching layer. The seeds were placed in the drums and top surface of bed adjusted to the horizon. The rotation of the drums began at a low speed (0.5 rpm) and gradually increased until observation of the slumping motion (figure 4, left). The rotation speed of drums was measured by laser photo/contact tachometer (Lutron DT-1236L, Taiwan). The avalanche of CS from upper to lower position in slumping motion was recorded by video camera. The video films were converted to images with 0.05 s intervals by using the Microsoft Windows movie maker software. Then the pictures were inserted in Solid works 2008 software and by fitting a straight line to the surface of the seeds bed, lower angle of repose (AR) and upper AR were measured (Figure 5).

It should be noted that the choice of the frames is somewhat subjective and needs experience. In order to reduce errors, the measurements were repeated three times [7].

In the next stage with higher increase in rotation speed, the time interval between the two avalanches in the slumping mode becomes shorter and the slope of the bed surface, dynamic AR (θ), remains approximately constant (Figure 4, right). Method of determining the dynamic AR is same as the method that was explained for determining angles of α and β by taking pictures from recorded films and measuring of angle by Solid works software.

In a brief statement, in present study the tests were conducted to determine the lower and upper AR of CS. The effects of filling degree (0.2, 0.3 and 0.4) and drum diameter (150, 180 and 300mm) were studied on upper and lower AR of CS. In this range of rotation speed, the seed bed was in the slumping mode. In the second set of the tests, the seed bed was set in the rolling mode and the effect of filling degree and drum diameter (as mentioned in three levels for the first set of tests) was studied on dynamic AR of CS.

Statistical Analysis: The experimental data were analyzed and processed by SPSS (Statistical Package for Social Science) 17.0 software. The differences between mean values were analyzed and presented using the Duncan test for comparison and effects were considered to be significant at $p<0.05$.

RESULTS AND DISCUSSION

Biophysical Properties of Corn Seeds: The mass and dimensional properties (mean, minimum, maximum and standard deviation) of the corn seeds (CS) used in this study are summarized in Table 1. The length of the seeds ranged from 8.05 to 14.45 mm, width ranged from 5.55 to 10.50 mm and thickness ranged from 3.05 to 8.20 mm.

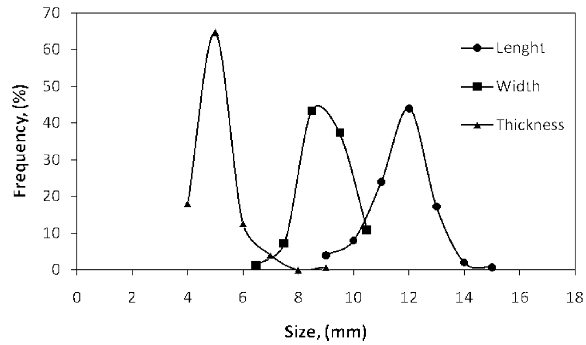

Fig. 6: Frequency distribution curves for CS dimensions at 8.5% (d.b.) moisture content

The geometric mean diameter of the seeds was 7.52 mm and the sphericity had a mean value of 0.68. The corn seeds had a bulk density of 753-763 kg/m^3. The results obtained in this study were in general agreement with those reported by Jayas and Cenkowski [20] for CS.

The following general expression was obtained to describe the relationship among the average dimensions of CS at 8.5% (w.b.) moisture content:

$$L = 1.328W = 2.56T \quad (4)$$

Where L is length of the seeds (mm), W is width (mm) and T is thickness (mm).

The size distribution of the CS is shown in Figure 6. It was observed that 54% of the seeds had a greater length than mean value (11.23 mm), 52% of the seeds had a greater width than mean value (8.53 mm) and 65% of the seeds had a greater thickness than mean value (4.53 mm). Figure 6 shows that frequency curves of length, width and thickness of CS have rather normally distribution.

Effect of Filling Degree and Drum Diameter on Angles of Repose: The experimental data showed that the slumping mode of motion was occurred in rotation speeds lower than 8.8, 6.2 and 4.9 rpm for three drums with 150, 180 and

Table 1: Mass and dimensional properties of CS

Parameter	Mean	Minimum	Maximum	Standard Deviation
Length, mm	11.23	8.05	14.45	1.03
Width, mm	8.53	5.55	10.50	0.80
Thickness, mm	4.53	3.05	8.20	0.73
Geometric mean diameter, mm	7.52	6.37	8.76	0.41
Sphericity,	0.68	0.52	0.95	0.04
Mass of 1000-seeds, g	254.54	273.8	296.9	9.78
Surface area of a single seed, mm^2	151.18	110.44	217.38	17.64
Volume of a single seed, mm^3	184.12	110.88	335.86	38.06
bulk density, g/cm^3	758.50	753	763	4.43
True density, g/cm^3	1244.80	1242	1246	1.89
Porosity, %	39.06	38.76	39.57	0.35

Table 2: Result of analysis of variance for the effect of filling degree and drum diameter on the lower, upper and dynamic angle of repose

		Mean Square Error, (MS)		
Source	df	Lower AR	Upper AR	Dynamic AR
Filling degree (f)	2	5.474*	28.302**	35.237**
Drum diameter (D)	2	5.384*	23.062**	23.239**
f×D	4	1.911^{ns}	0.58^{ns}	8.340^{ns}
Error	18	3.387	1.160	3.882

ns: not significant; ** significant at 1% level; * significant at 5% level

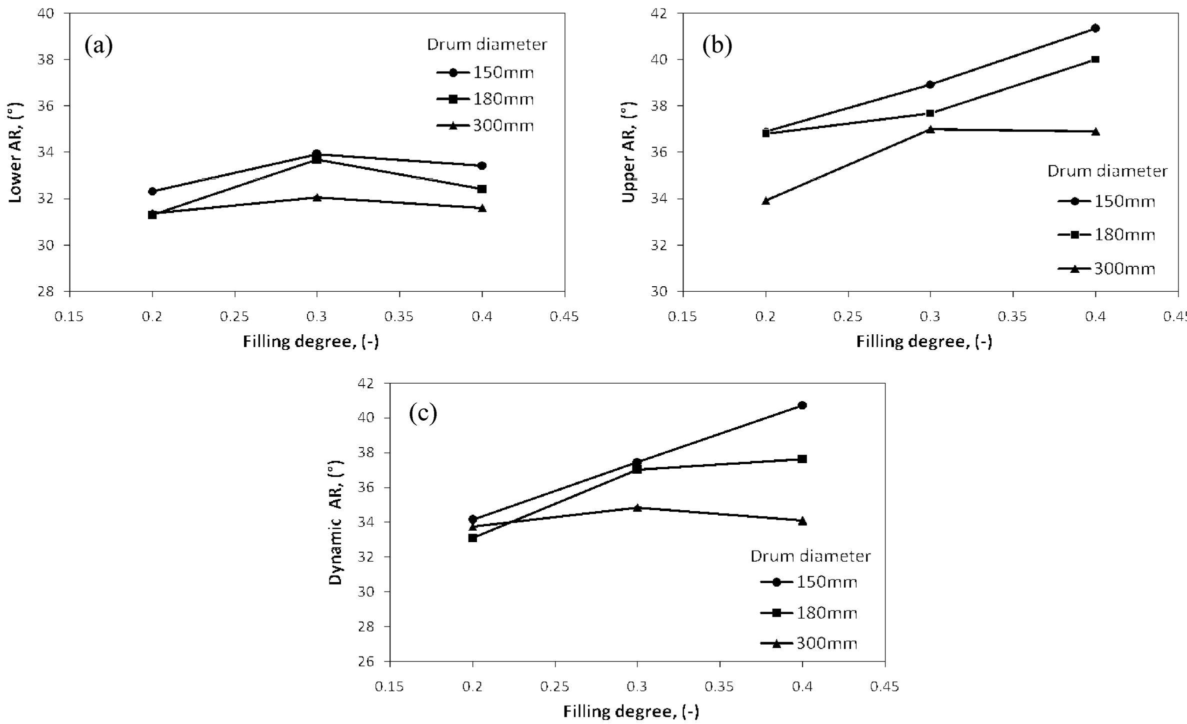

Fig. 7: Effect of filling degree and drum diameter on the lower AR (a), upper AR (b) and dynamic AR (c) of CS.

300 mm diameter, respectively (Figure 4, left). Analysis of the data also showed that the rolling mode was occurred at rotation speeds of 4.9 to 44.2 rpm ($Fr=8.05\times10^{-3}$-0.328) depending on drum diameter and filling degree (Figure 4, right). Cristo *et al*. [1] have also reported similar results for coffee beans. Dury *et al*. [21] found that for mustard seeds (d = 2.5mm) there was a transition from slumping to rolling around $Fr = 1.2\times10^{-3}$ when drum diameter was 69 mm.

Results of analysis of variance for the effect of filling degree and drum diameter on the angles of repose of CS are shown in Table 2. Analysis of variance indicated that both the filling degree and drum diameter had significant effects on the upper, lower and dynamic Angle of repose (AR) of CS. As shown in table 2, the interaction effect of filling degree and drum diameter had no significant effect on lower, upper and dynamic AR of CS (Figure 7).

Liu *et al.* [7] found that the effect of the filling degree on upper and lower AR of glass beads (d=3, 5mm) was negligibly small. In contrast the drum diameter exerted more influence. Khazaei and Ghanbari [14] reported that filling degree has significant effect on upper and lower AR of wheat seeds with geometric mean diameter of 4.03 mm.

The difference in results of various materials (agricultural and engineering) can results from bed behavior of granular materials. The behavior of granular material bed affected from various biophysical characteristics such as size, shape, mass and dimensional properties of particles [3]. These biophysical characteristics for CS used in present study has measured and shown in Table 1.

Except the researches of Khazaei *et al*. [5] and Khazaei and Ghanbari [14] it was found no published paper on studying the effect of filling degree and drum

Table 3: Mean values of lower, upper and dynamic AR of CS at different filling degrees, drum diameters and ratio of particle to drum diameter

Main parameter	Lower AR (degree)	Upper AR (degree)	Dynamic AR (degree)	$(\alpha+\beta)/2$ (degree)
Filling degree, (-)				
0.2	31.7A*	35.9A	33.7A	33.8
0.3	33.2B	37.9B	36.4B	35.6
0.4	32.5AB	39.4B	37.5B	36.0
Drum diameter, (mm)				
150 (d/D=0.0501)	33.2A	39.1A	37.4A	36.1
180 (d/D=0.0418)	32.5AB	38.2A	35.9AB	35.3
300 (d/D=0.0251)	31.7B	36.0B	34.2B	33.8

* Means with the similar letter have no significant difference at p=0.05.

diameter on dynamic AR of seeds and grains in slumping mode. In the mentioned study the effect of filling degree on the calculated dynamic AR of wheat seeds was significant. Result of our study for the effect of filling degree on dynamic AR of CS is in agreement with the investigation on dynamic AR of wheat seeds reported by Khazaei and Ghanbari [14]. For engineering granular materials Yang *et al.* [22] reported an increase in dynamic AR measured in rolling mode with increasing drum speed.

The results of the experiments on determining the lower, upper and dynamic AR of CS are shown in Table 3. The mean values of lower AR, upper AR, dynamic AR and calculated dynamic AR (using Equation 3) of CS for each level of drum filling degree, drum diameter and ratio of particle to drum diameter are shown in Table 3. The mean values of lower, upper, dynamic and calculated dynamic AR of the seeds were 32.5, 37.7, 35.9 and 35.1 degrees, respectively. Corresponding values of standard deviations were 0.78, 1.77, 1.98 and 1.16 respectively. These low standard deviations confirm the accuracy and repeatability of the tests. However, as reported by Liu *et al.* [7] it is almost impossible to measure the lower and upper AR with an error lower than 0.5°.

From the results shown in Table 3, with increasing the filling degree from 0.2 to 0.3, the mean values of lower, upper and dynamic AR of CS were increased from 31.7° to 33.2°, 35.9° to 37.9° and 33.7° to 36.4° respectively. The difference between the mean values of angles of repose at filling degree of 0.2 and 0.3 was significant at 5% level. With higher increase in filling degree from 0.3 to 0.4 the lower, upper and dynamic AR showed non significant decreasing and/or increasing trends.

With increasing the drum diameter from 150 to 180 mm, the difference between the mean values of angles of repose was not significant at 5% level, but with higher increase in drum diameter from 180 to 300 mm the mean value of upper AR had significant decreasing trend meanwhile the mean values of lower and dynamic AR was not significant (Table 3, Figure 7).

Comparison of directly measured values (from rolling motion) with calculated values (from Equation 3) for dynamic AR (θ) of CS by T test showed that there is no significant difference between the measured and calculated values. This means instead of measuring of dynamic AR of CS in rolling motion, we can calculate θ from Equation 3.

For all materials investigated, the lower AR varies between 22° and 39° and the upper AR between 23° and 44°. The values depend strongly on the shape and the surface roughness of the particle [23]. Round and smooth particles have smaller AR, when other parameters are kept constant.

The mean values of lower, upper and calculated dynamic AR of wheat seeds, reported by Khazaei and Ghanbari [14], were 30.2, 35.2 and 32.7 degrees, respectively. Steel balls and fertilizer pellets investigated by Liu *et al.* [8] had also an upper AR of 34.97° and 40.7°, respectively. Henein *et al.* [16] concluded that the upper AR of all materials they investigated was greater than 32°. It can be said that there is a general agreement between the data of Table 3 and data of other researches on various materials.

Correlation Between Size Ratio (d/D) and Angles of Repose: From the results of Table 3, with increasing the size ratio (d/D) from 0.0251 to 0.0501, the mean values of lower, upper, dynamic and calculated dynamic AR of CS were increased significantly from 31.7° to 33.2°, 36.0° to 39.1°, 34.2° to 37.4° and 33.8° to 36.1° respectively.

Ghanbari *et al.* [24] investigated the effect of d/D on lower and upper AR of rice seeds with geometric mean diameter equal to 2.74 mm. They found that d/D had increasing effect on lower and upper AR. Henein *et al.* [16] in their research on limestone (d=0.58, 1.5, 4.3, 8.1 mm), found that the d/D had increasing effect on both the lower and upper AR. Increasing effect of d/D on lower and upper AR of glass beads is reported by Liu *et al.* [7], too.

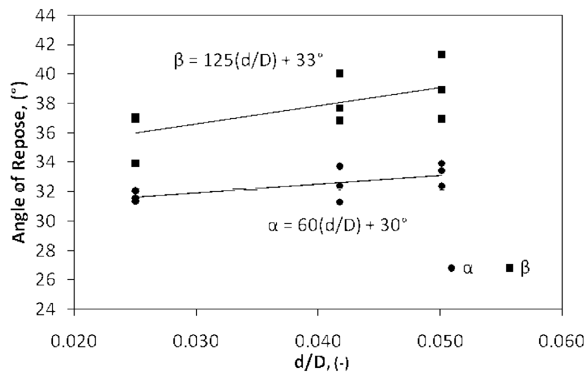

Fig. 8: Correlation between size ratio (d/D) and lower and upper AR of CS.

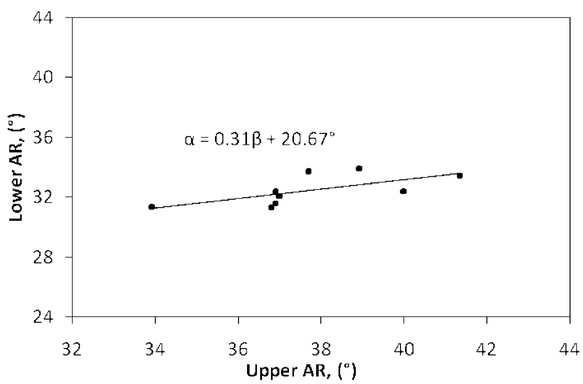

Fig. 9: Correlation between the lower and upper AR of CS.

In Figure 8 the size ratio (d/D) is plotted against AR of CS. The data points in this figure correspond to all of the values of filling degrees (0.2, 0.3 and 0.4). By fitting a linear trend line to the data points, correlations of d/D and α and β are obtained:

$$a = 60(\frac{d}{D}) + 30° \tag{5}$$

$$\beta = 125(\frac{d}{D}) + 33° \tag{6}$$

In Figure 8 as the d/D increases, the β increases more steeply than α. The greater slope of correlation of β (125) rather than α (60) in Figure 8 shows this subject. Consequently, the difference between the two angles (β-α) increases with d/D. For the CS, the differences measured between the lower and upper AR (β-α) lies in a small range of 4.2 to 6.9°, depending on the filling degree and drum diameter (Table 3 and Figure 8). Similar results for β-α of rice seeds reported by Ghanbari *et al.* [24]. They found that the value of β-α was variable from 2.4° to 7°. Khazaei and Ghanbari [14] for wheat seeds and Davidson *et al.* [15] for sand found that the value of (β-α) scatters in a range from 1.34 to 7.65° and 2 to 4° respectively.

Correlation Between Lower and Upper Angle of Repose: The experiments results showed that the upper and lower AR depend on each other as shown in Figure 9. The results of upper and lower AR are useful in practice and in mathematical modeling to predict the critical Froude number for transition from slumping to rolling mode of motions for CS.

The lower AR depicted versus upper AR of CS in Figure 9. The data points in this figure correspond to all of the values of filling degree (0.2, 0.3 and 0.4). By fitting the values in Figure 9 to a linear function, following correlation is obtained:

$$\alpha = 0.31\beta + 20.7° \tag{7}$$

It should be noted that Equation 2 is only valid for β>34°. Similar results have been reported by Khazaei and Ghanbari [14] for wheat seeds (Equation 8), Ghanbari *et al.* [24] for rice seeds, Liu *et al.* [7] for glass beads (Equation 9), Dury *et al.* [21] for mustard seeds and Henein *et al.* [16] for limestone. From these works, for example two cases are:

$$\alpha = 0.77\beta + 2.82° \tag{8}$$

$$\alpha = 0.65\beta + 8.75° \tag{9}$$

As can be seen these correlations are very similar to Equation 7. The Equation 7 together with the Equation 3 for the dynamic AR could be very useful in practice in that only one angle has to be measured instead of three.

CONCLUSIONS

Based on the experimental work, the following conclusions have been drawn:

- The mean values of lower, upper, dynamic and calculated dynamic angle of repose (AR) of corn seeds (CS) were 32.5°, 37.7°, 35.9° and 35.1°. These values are in the range of different AR for various materials and seeds investigated by other researchers.
- The difference between the Upper AR and lower AR (β-α) of CS ranged between 4.2° to 6.9° depends on the filling degree and drum diameter (and size ratio).

This difference is in the range 2-7° reported by Henein *et al*. [16].

- Both the factors of filling degree and drum diameter had significant effect on the lower, upper and dynamic AR of CS.
- Particle to drum diameter ratio (d/D) had significant and increasing effect on the lower, upper and dynamic AR of CS.
- Equation $\theta = \frac{\alpha + \beta}{2}$ (Equation 3) is reliable for determining of dynamic AR of CS. Calculation of θ by Equation 3 decreases our measurements and consequently decreases the measurement errors and so by just measuring of α and β in slumping motion, θ can be calculated from Equation 3.
- It is found that the lower (α) and upper (β) AR are not two independent parameters. Instead, they are two dependent variables. Based on measurements from this work, a linear correlation $\alpha = 0.31\beta + 20.7°$ α (β>34°) is obtained. This correlation together with the equation for the dynamic AR $? = \frac{a + ß}{2}$ is very useful in practice in that only one angle has to be measured instead of three.

ACKNOWLEDGEMENT

The authors would like to thank the University of Tehran (Department of Agro-Technical Engineering, College of Abouraihan) for technical supporting of this work.

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