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The Coriolis Effect on Spherical Particles Inside the Bowl

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Abstract— An innovative mechanism is presented for granulation of sago particles. This study aims to express more closely the Coriolis effects in a granular medium. The results of analytical models with and without considering Coriolis force are compared and validated with the experimental results. The analytical results coincide with experimental results with average negligible error (4 - 6 %) in case of Coriolis forces are considered and with significant error (9 - 12 %) if not considered. The Coriolis force will support to the mass build up of the particles by affecting the centrifugal motion.

Keywords*— Bowl, Granulation, Particle, Coriolis force.*

I. INTRODUCTION

Sago is an edible starch obtained from cassava roots. It is dried to produce flour and then processed into granular form. The sago starch is a very nutritious product which contains essential nutrients like carbohydrates along with appreciable amount of calcium and vitamin C. It is cultivated mostly in the South Indian states of Kerala and Tamil Nadu [1]. The starch industry has been developed during the last five decades in India especially around Salem (Tamil Nadu). The advantages of this mechanism over the existing conventional methods are reduction in individual machineries employed and skilled labour requirement [2].

II. RELATED WORK

The studies have been performed on the granulation techniques and particle dynamics with and without considering Coriolis component in various applications. Heim et al. [3] showed that the values of reduced torques are higher for big diameter disc in the disc granulation process and the angle of disc inclination on the reduced torque was observed significantly. Aphale et al. [4] made experimental and analytical studies to investigate particle trajectories on and off a spinner spreader. Analytical models for the on-spinner and off-spinner trajectories were also presented and the experimental data for on-spinner particle trajectories generally lie between the analytical models for the pure rolling and pure sliding conditions using a sliding friction coefficient of 0.5. Rioul et al. [5] presented a dynamical transition between a rolling and sliding and also the purely sliding regime as function of the friction coefficient and elongation of the particle. Grift et al. [6] analysis showed that the friction coefficient can be measured using a single radial velocity measurement of particle at a distance of 4.0 m from the edge of the disc. The experiments were carried out using single disc spreader. The data showed that the larger particles attained slightly higher velocities than did smaller ones, and the friction coefficients showed a moderate inverse relationship with the particle diameter.

Andrei Craifaleanu et al. [7] developed mathematical model with Coriolis component for the motion of particles on the conical vibrating sieve to determine the non linear equations. Shrisath et al. [8] presented the dry granular flows down a rotating chute inclined at angle of 30° in which the particle velocity is slightly reduced in the first half length of the chute as result of the Coriolis force and increases in the second half due to the effect of centrifugal forces. Samik Nag et al. [9] presented mathematical simulation of material trajectory and concluded that Coriolis force has significant effect on the motion of the particle and it increases the frictional force. Rioual et al. [10 - 11], studied the flow of the grains along a rotating plane in which the packing flows under the effect of the rotating boundary driven by the Coriolis and centrifugal force in the spreading of a dry granular material and Coriolis stress depends on the height of the pile. Dorbolo et al. [12] showed that while the system is rotating, a grain placed on the plate moves away from the center of rotation, i.e., towards a side of the plate Coriolis force plays an important role here and a low speed condition avoids the Coriolis force. Dintwa et al. [13] showed that, four major components are involved for a particle on a spinning disc: the rolling inertial force, the frictional force, the centrifugal force and the Coriolis force for a clear explanation.

Grift et al. [14] presented that, the gravitational acceleration is absent in the particle dynamics equation, since the gravitational force is very small compared to the horizontally acting Coriolis force. Higher rotational velocities exert larger Coriolis forces on the particles, resulting in the particles being pushed more firmly onto the sidewall thereby reducing the oscillation magnitude. Warnett et al. [15] explained that, due to the Coriolis effects, the particulate moves in a positive azimuthal direction within the rotating frame of reference while flowing radially outwards, resulting in curvature of the runout. Thomas and Zoueshtiagh [16 - 17], presented the granular ripple under the rotating flow in which the Coriolis forces on moving grains can be incorporated by an appropriate term in the expression for the flight length. This force only becomes effective, however, once the grains are in motion. Thus, it only acts after the system has selected its onset wavelength. In Paul Van Liedekerke's [18] thesis, when the radial velocity of a particle on a rotating disc is nonzero, the Coriolis force comes into play. The particle is accelerated in the radial direction by the centrifugal force and hence a radial velocity builds up which is responsible for the Coriolis force. Basu et al. [19] derived the displacement equation of motion in the rotating frame with the centripetal acceleration and Coriolis acceleration. Manuel Feliz - Teixeira [20] clearly demonstrated that the centrifugal, Coriolis and Euler forces are real forces, therefore they should not be called fictitious and it will be sufficient that people start to consider these forces as real, so that new studies and proposals in the scientific and technological domains will naturally emerge.

III. MECHANISM AND MODELING

Sago sizing process is a size growth technique whereby very fine particles are gathered into larger aggregates of particles. In this technique, the water is added to the sago powder and the liquid films developed by the addition of binder causes the sago powder particle to adhere with each other. This process leads to the formation of aggregates and growth of sago granules. The formation of agglomerates and growth of granules can be described by two mechanisms viz. nucleation of particles, coalescence between agglomerates [21]. The mechanism of mixing of sago powder and water is shown in figure 1. The growth of cassava pearl was very sensitive to binder content and the binder content increased the particle size enlargement decreased [22].

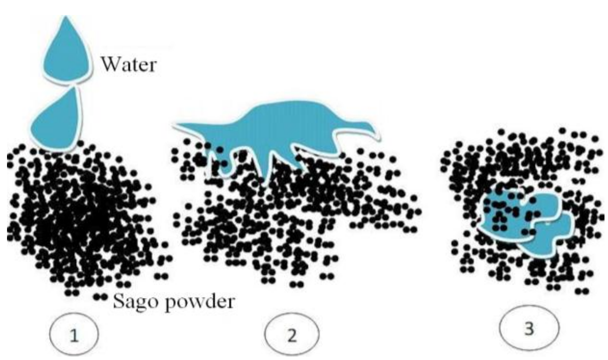

Figure 1. Sago powder and water mixing process

The dynamic analysis of spherical particles inside the bowl is described by rolling, sliding and bouncing [2]. In this paper only rolling motion of the spherical particle is considered for the analysis. The principle of the mechanism and motion of particles on the bowl is shown in figure 2. In this bowl the sago powder and water mixes with each other and to attain the roughly spherical shape granule. The globule of sago granules roll over the edge of the bowl and finally thrown out from it. Thus the uniform spherical shape of sago is achieved. This study describes the mathematical models of motion of completely developed rolling particles on the rotating bowl. The system of forces acting on the particle under the rolling are; applied force through the bowl, centrifugal force, frictional force and also the Coriolis force. The Coriolis component plays major role in the particle dynamics inside the bowl when the particle rolls on the bowl surface since the bowl which rotates with two different speeds viz. bowl spinning about its own center axis and the precession of the rod about vertical axis.

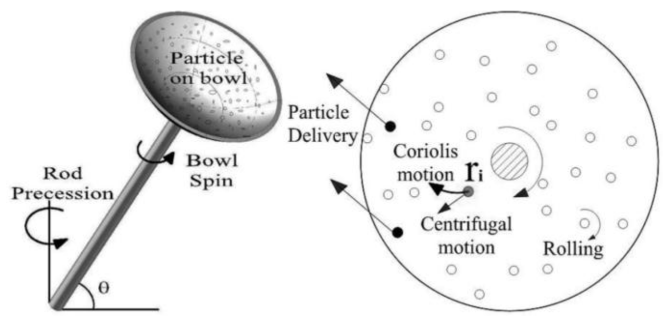

Figure 2. Schematic of mechanism and particle motion on the bowl

In this mechanism the behaviour of the rolling particles is described by the analysis of force system using the D' Alembert principle and Newton second law of rotation. As per the D'Alembert's principle for translational motion the force system states that,

$$\sum F + m\,(d^2r/dt^2) = 0 \qquad (1)$$

The bowl is driven by spin and precession rotation then the rotational speed of the bowl will be,

$$\omega = [(\omega_1 \sin\theta)^2 + (\omega_1 \cos\theta + \omega_2)^2]^{0.5} \qquad (2)$$

Apply the Newton's second law of rotation for spherical particle;

$$I\,\ddot{\alpha} = F_a\, r_p \qquad (3)$$

Thus the analytical models with and without considering Coriolis force are prepared, compared and validated with the experimental models.

A. Modeling without Coriolis force

The forces acting on the particle without Coriolis force are; applied force through the bowl, centrifugal force, frictional force between the particle and bowl surface. The sum of force acting of the rolling particle can be resolved along the curved path is given in the equation 4,

$$m.a = -F_a + F_c - F_R \quad (4)$$

The rolling dynamics of spherical shaped particles can be derived as a second order differential equation by using the equations 1- 4 and it is given by,

$$(d^2r)/dt^2 = (mr_p^2 (r\omega^2-\mu g)) / (I+ mr_p^2) \quad (5)$$

Applying initial conditions; $r_{t=0} = r_i$ and $\dot{r}_{t=0} = 0$; The instant radial position of the particle is given by,

$$r = \cosh (0.845\ \omega t)\ r_i + \mu g/\omega^2 [1-\cosh (0.845\ \omega t)] \quad (6)$$

The radial velocity of the particle can be obtained as in the equation 7 by differentiating the equation 6,

$$\dot{r} = 0.845\sinh (0.845\ \omega t) [\omega r_i - \mu g/\omega] \quad (7)$$

B. Modeling with Coriolis force

The Coriolis force is considered for this analysis since the particle rolls on the rotating bowl driven by two different rotational speeds consists of the bowl spinning about its own center axis and the precession of rod about the vertical axis. Here the system of forces acting on the particle under the rolling are; applied force through the bowl, centrifugal force, frictional force and also the Coriolis force. The sum of force acting of the rolling particle can be resolved along the curved path is given in equation 8,

$$m\ a = -F_a + F_c - F_{Cor} - F_R \quad (8)$$

The equation 8 can be derived as a second order differential equation similarly as equation 5 and it is given by,

$$d^2r)/dt^2 = mr_p^2 (r\omega^2- \mu g - 2\mu\omega.dr/dt) / (I+ mr_p^2) \quad (9)$$

Applying Initial conditions; $r_{t=0} = r_i$ and $\dot{r}_{t=0} = 0$; The instant radial position of the particle is given in equation 10 and the equation 6 and equation 10 are used to determine at which position the particle will getting off from the bowl for without considering and with considering the Coriolis force respectively.

$$r = 0.5(r_i - \mu g/\omega^2) \exp \{(-0.714)\ \mu + 0.845\ (1+0.714\ \mu^2)^{0.5}\}\ \omega t + 0.45(r_i - \mu g/\omega^2) \exp \{(-0.714)\ \mu - 0.845\ (1+0.714\ \mu^2)^{0.5}\}\ \omega t + \mu g/\omega^2 \quad (10)$$

The radial velocity of the particle can be obtained as in the equation 11by differentiating the equatio10,

$$\dot{r} = 0.5(r_i - \mu g/\omega^2) \exp \{(-0.714)\ \mu + 0.845\ (1+0.714\ \mu^2)^{0.5}\}\omega t. \{(-0.714)\ \mu + 0.845\ (1+0.714\ \mu^2)^{0.5}\}\ \omega + 0.45(r_i - \mu g/\omega^2) \exp \{(-0.714)\ \mu - 0.845\ (1+0.714\ \mu^2)^{0.5}\}\ \omega t. \{(-0.714)\ \mu - 0.845\ (1+0.714\ \mu^2)^{0.5}\}\ \omega \quad (11)$$

The total velocity of the particle can be written as,

$$V = ((\dot{r}^2) + (\omega R)^2)^{0.5} \quad (12)$$

These equations are used to describe the rolling dynamics of sago particle on the rotating inclined bowl with various rotational speeds and to determine the total residence time of the particle numerically.

C. Experimental model

The experiments are performed to determine the dynamics of the particles and residence time for different rotational speed of the bowl. The experimental setup includes the bowl with the different sizes, rod with the different inclination angle, gear setup, dc motors, control unit, sensors, bearings, joints and linkages for providing the spin rotation of the bowl, precession rotation of the rod and inclination of the rod as shown in figure 3. The bowl and rod rotated using the drive mechanism which is connected with the two DC motors. The rotational speeds of the bowl and rod are determined and controlled with the proximity sensors and control unit respectively. The control unit attached to the experimental setup is interfaced with the computer. The data received from the control unit is in the form of serial data.

The experimental procedure starts with the sago powder preparation from the cassava roots. The cassava roots are weighed in the water bucket to determine the amount of sago present in the roots and the sago flour extracts from the roots. The volume of the bowl is ranges from 1200 cm^3 to 1440 cm^3 and the bowl can be filled with 0.2 - 0.25 kg of material approximately for better granulation. The particle mass for the sago balls are obtained from the preliminary experiments ranges from 0.09×10^{-3} to 0.21×10^{-3} Kg. Also the preliminary experiments are done for determining the friction coefficient using the inclined solid block. The friction coefficient values of the particle close to the range of 0.35 - 0.45 and average of 0.4. The experiments are carried out for the following parameter viz. 60° inclination angle of rod, coefficient of friction of 0.4 and 150, 200, 250, 300 mm size of bowl with rotational speed of 0.5 to 3.6 rad/s. The angle of inclination of rod with the horizontal axis is 60° and the correction factor for the static and dynamic condition of the bowl is 0.029 [2, 23]. Also the following parameters are not considered for this study such as, sliding friction, normal reaction, air resistance and the surface roughness of the bowl.

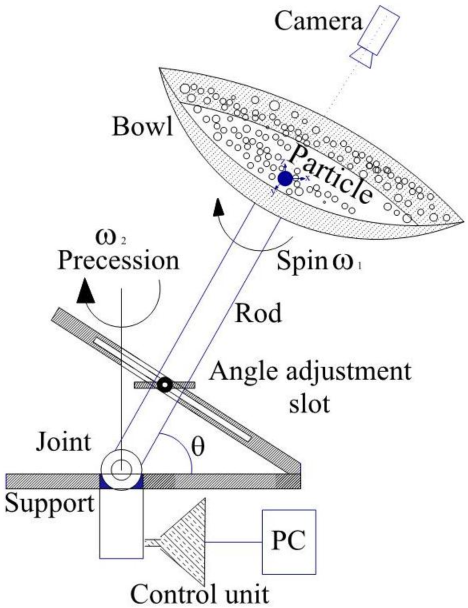

Figure 3. Experimental setup

IV. Results and Discussion

The study of the spherical shaped particles on the rotating bowl is carried out. The visualization of force distribution on the particle obtained from the experiments under the minimum (0.5 rad/s) and maximum (3.6 rad/s) rotational speeds of bowl is shown in figure 4. The force system on the particle is found to be more homogeneous in the case of least rotational speed due to large gravity acting on the particle and it is observed that the minimum Coriolis action on the particle. When the rotational velocity of the bowl is more, the particle mass overcome the gravity and it is responsible for the major role of the Coriolis force. Hence the role of Coriolis force is least for the lowest rotational speed of the bowl. But the lowest rotational speed of the bowl will affect the amount of particle thrown out from the bowl, since the particle thrown out strongly depends on the rotational speed of the bowl and mass of the particle.

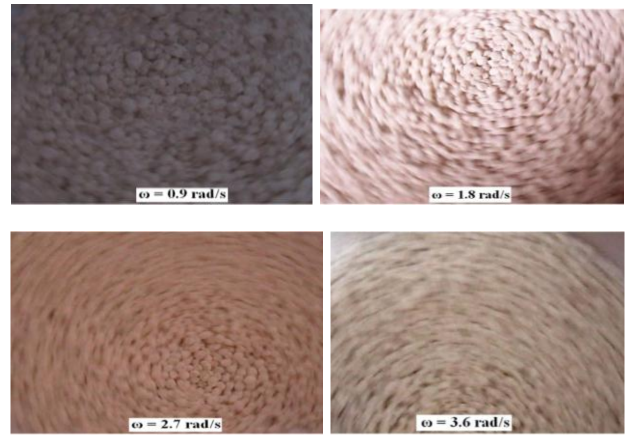

Figure 4. Particle motion on the bowl due to force distribution; ω = 0.9, 1.8, 2.7 and 3.6 rad/s.

The radial positions of the particle with respect to time for 3.6 rad/s rotational speed of bowl are shown in figure 5 and it is observed that the particle reaches the end position slowly with considering Coriolis component and quickly without considering Coriolis force. The results of analytical models with considering Coriolis force are well matching with the experimental results with practical error of 5 – 7%. It may true to conclude that the Coriolis component will resist the centrifugal motion of the particle. From the results of the mathematical models and experimental results, the relation between the total velocity of particle and rotational speed of the bowl with different sizes is presented. The total velocity of the particle increases with increase in the rotational speed of the bowl. For a given rotational speed, the total velocity of the particle is more for without considering the Coriolis force component compared to with considering the Coriolis force component as shown in figure 6. The results of total velocity of the particle with considering Coriolis component are coincide with the experimental results. The difference between these analytical and experimental data is about 3.5%.

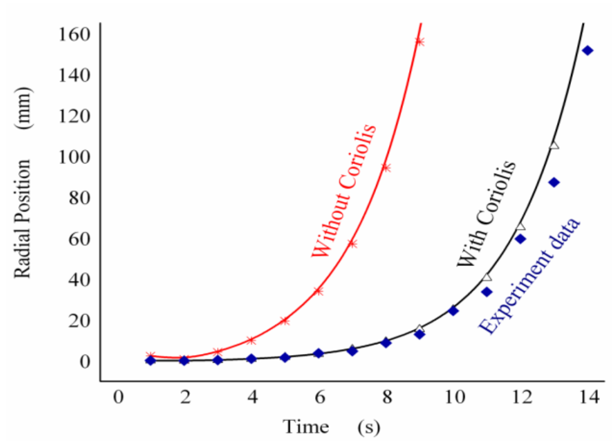

Figure 5. Radial position of the particle

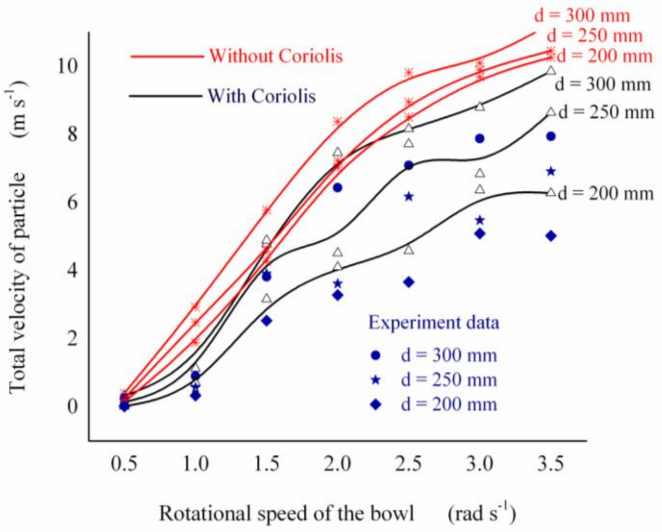

Figure 6. Total velocity of the particle

The total time of particle to reach the bowl edge and getting off from the bowl is reduced by increasing the rotational speeds of the bowl as shown in figure 7. The experimental results and the analytical results with considering the Coriolis component are matched with the negligible error of 4.5 %. Thus the residence time is more when considering the Coriolis force component and it is least for without considering Coriolis force component for a given rotational speed. The results of analytical models varies with the experimental results are 9-12% in the case of absence of Coriolis component and 4-5 % in the case of presence of Coriolis force. It is observed that the particle is quickly reached of bowl edges with highest total velocity of particle for absence of Coriolis force. Thus the variation of total residence time of particle of the experimental results is insignificant for the presence of Coriolis force and significant for the absence of Coriolis force.

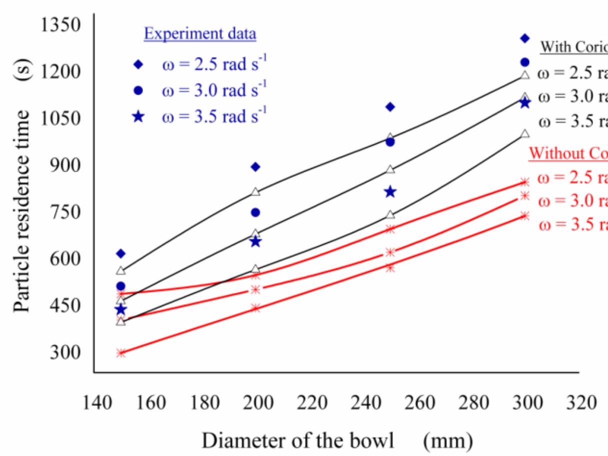

Figure.7 Residence time of the particle

V. Conclusion

This study asserts that the dynamic behaviour of rolling sago particles on the bowl of different diameters and different rotational speeds. When the angular velocity of the bowl is increased then the total velocity of the particle is also increased. As the total velocity of the particle is increased the rate of particle delivery is more for any size of the bowl. It is concluded that the residence time of particle on the bowl is minimum for maximum rotational speed of the bowl. For the 60° angle of inclination of rod, the Coriolis component affects the all parameter in the dynamic behaviour of rolling particle significantly. The mathematical models are validated using the experimental model in which the analytical models with considering the Coriolis component matched with the experimental results by 4 - 6 % average variation and the results of absence of Coriolis force significantly vary with the experimental results by 9 - 12%. Thus the Coriolis force is a functional phenomenon for the better granulation since the Coriolis force will increase the residence time by affecting the centrifugal motion of the particle and it enhances the mass build up of the particles.

Nomenclature

F_a	force applied to the rolling particle
F_c	centrifugal force acting on the particle
F_{Cor}	Coriolis force acting on the particle
F_R	rolling frictional force acting on the particle
g	acceleration due to gravity
m	mass of the particle
μ	friction coefficient between particle and bowl
R	radius of the bowl
r_p	particle radius
t	instant time
I	moment of inertia of the particle
θ	inclination angle of the rod with horizontal plane
α	angular position of the particle
$\ddot{\alpha}$	angular acceleration of the particle when rolling
a	linear acceleration of the particle
ω_1	precession of the rod
ω_2	spin of the bowl
ω	rotational speed of the bowl
r	radial position of the particle from the center of bowl
r_i	initial radial position of the particle
$\dot{r}$	radial velocity of the particle
v	total velocity of the particle when its leaves the bowl

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