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Rolling and bouncing dynamics of particles in the inclined rotating bowl for sago sizing mechanism

S.M. Raj Kumar [a,*], R. Malayalamurthi [b], R. Marappan [c]

[a] Erode Builder Educational Trust's Group of Institutions, Tirupur, Tamilnadu, India
[b] Government College of Engineering, Salem, Tamilnadu, India
[c] K.S.R. College of Engineering, Namakkal, Tamilnadu, India

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ABSTRACT

A novel mechanism for automatic sizing of sago granules is presented in this paper with analytical and experimental studies. This automation method would help to overcome the difficulties faced in the conventional labor which is the intensive process of sago sizing. This paper mainly discusses the data required to define the particle trajectory and behavioral movement in shaping the sago granules. Mathematical models are prepared and experimental studies are performed for the instant at which the flight of particles will occur due to centrifugal flee force and for the trajectory of the particle dynamics for various rotational speeds of the bowl and inclined rod that is coupled to the bowl. The prepared range of inclination angle of the rod is 60° to 64° with the horizontal plane. The maximum flight velocity of particle with a maximum height for models and experiments is 9.81 m/s for the height of 46.43 mm and 9.8 m/s for the height of 43.12 mm. The total residence time of the particle inside the bowl diameter of 200 mm and height 50 mm is also determined numerically as 6 min 43 s and experimentally as 7 min 15 s for the initial radial position of the particle of 20 mm from the axis of rotation of the bowl. The results of analytical models are compared and validated with the experimental results and the analytical results coincide with experimental results with negligible amount of error.

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1. Introduction

Tapioca Sago, generally known as sago in India is prepared from the milk of tapioca root. The crop is widely known and recognized by several names in the various regions where it is grown. The tapioca roots contain about 60–70% moisture, 20–31% carbohydrate, 7–12% protein, 5–13% starch and comparatively low content of vitamins and minerals. About 13 states in India cultivate the crop and especially the South Indian states of Tamil Nadu and Kerala are the major producers. Currently the small scale industries of Tamil Nadu stand first in processing of tapioca into starch and sago in India. Starch and sago production from India is projected to attain 0.4 and 0.3 million tons respectively by the year 2020 [1]. Hence to meet the market demands, small scale industries involved in sago products require new mechanisms to reduce processing time and labor requirements and to minimize individual machineries employed. In general, the products from tapioca like starch and sago were prepared manually on a cottage scale basis in India with lengthy process such as fleshing the tapioca roots, extracting and settling the milk, forming, granule sizing and roasting the granules. The granule sizing is the more time consuming process compared with others. Conventionally the granule sizing of wet starch is agglomerated in a cloth cradle which is used as a granulator until larger granules are formed [3] or bucketing wet starch in a strainer plate which slides or rotates to form granules. In the cloth cradle granulation skilled labor is required, since the quality and quantity of sizing are strongly dependent on labor skill. In the strainer plate sizing process, the range of sago sizes is obtained by changing the strainer plate to the required size. To overcome these conventional methods an automation method is devised for sizing of the particles and it is used to acquire globule form of sago based on the rotational speeds. This new automatic sago sizing mechanism presented here can produce and deliver sago granules of various dimensions by varying the rotational speeds of the bowl and inclination of the rod. This mechanism will provide better quality of granules than the conventional methods, since the mechanism does not require skilled labor.

The dynamics of granulated sago particle inside the bowl is analyzed through the models and experiments in this paper. Several analytical and experimental studies have been conducted by researchers, over a wide range of application for particle trajectories at various rotational speeds and also for processing of granulation techniques. Kamal et al. [2] replaced the method of extracting sago starch by integration of

* Corresponding author at: Department of Mechanical Engineering, Faculty of Engineering, Erode Builder Educational Trust's Group of Institutions, Tirupur, Tamilnadu, India - 638108. Tel.: +919940981644.
E-mail addresses: kumar_tpm@yahoo.com (S.M. Raj Kumar), malayalamurthi_r@yahoo.com (R. Malayalamurthi), marrapan_r@yahoo.co.in (R. Marappan).

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Nomenclature

R	radius of the bowl
h	height of the bowl
L	length of the rod
θ	inclination angle of the rod with horizontal plane
r_p	radius of the particle
m	mass of the particle
g	acceleration due to gravity
μ	friction coefficient between particle and surface
α	angular position of the particle when rolling
R_n	radial position at which particle starts to fly
F_c	centrifugal force of the particle
W	weight of the particle
F_f	flight force acting on the particle
M_f	moment of flight of the particle
V_e	escape velocity of the particle
t	instant time
r_i	initial radial position of the particle
r	radial position of the particle at the instant time
$\dot{r}$	radial velocity of particle at the instant time
r'	new radial position of the particle in space
ω_1	precession rotation of the rod
ω_2	spin rotation of the bowl
ω_b	rotational speed of the bowl
V_b	linear velocity of the bowl
V_t	tangential velocity of the particle
V_p	linear velocity of the particle
$V_{p/b}$	relative velocity of the particle with bowl
V_{pf}	final velocity of the lifted particle
a	particle acceleration
E_r	energy required for lifting the particle
E_s	energy supplied to the particle
β	angle of flight of the particle
δ_h	roughness of the bowl surface
C_d	coefficient of air drag
A	frontal projectile area
x,y,z	location of particle in the spatial coordinate
P, P′	particle positions in the spherical coordinates
e_r	unit vector along the radial position r
e_θ	unit vector along the angular position θ
$\underrightarrow{e_\alpha}$	unit vector along the angular position α
$\vec{i}, \vec{j}, \vec{k}$	unit vectors along the x, y and z coordinates
T	transformation matrix of new position

both blending and mechanized squeezing into one unit aided by controlled amount of water. Labor and energy requirements could also be reduced reasonably owing to the fact that a few separate steps are combined into a single unit operation. Chansataporn and Nopharatana's [3] experimental results indicated that the growth of cassava pearl was very sensitive to binder content. At the initial stage to granulation stage (4 min), cassava pearl obtained from all treatments exhibited the maximum growth rate. The results also showed that particle size enlargement decreased as the binder content increased and the growth behavior of cassava pearl is dependent on drum filling degree. From the observation of Heim et al. [4] it was noted that the value of reduced torques is higher for big diameter disk in the disk granulation process and also the angle of disk inclination on the reduced torque was observed significantly. Heim et al. [5,6] proposed the model for bed dynamics during the drum granulation by dimensionless equations. They also showed a significant effect of bed wetting parameters on the kinetics of wet drum granulation and presented the effect of jet break-up on the granule related to surface tension. Hema [7] developed a simulation tool based on DEM of the granular motion based on solving Newton's equation of motion for each particle in the granular bed of horizontal rotating cylinder subjected to collisional forces, external forces and boundary forces. At every instant of time, the forces are tracked and the positions, velocities and accelerations of each particle are also studied.

Aphale et al. [8] conducted an experimental and analytical study to investigate particle trajectories on and off a spinner spreader. Analytical models for the on-spinner and off-spinner trajectories are 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 with a sliding friction coefficient of 0.5. Rioual et al. [9] presented a dynamical transition between rolling and sliding at the regime and also the purely sliding regime as a function of the friction coefficient and elongation of the particle. Rioual et al. [10] studied the trajectory of solid spherical particle bouncing at high velocity along the rotating plate with accurate statistical analysis of the trajectory for both radial and angular velocity and also showed that the bouncing trajectory consists of a succession in rebounds of decreasing height followed by a permanent contact of the particle along the vane. Wagenaar et al. [11] presented a mathematical model for a single particle description in the rotating cone reactor and observed the residence time of the particle inside the reactor experimentally. Based on the results, it was observed that the trajectory shape for larger particle is independent of the particle diameter; cone rotational speed and residence time strongly depended on the particle diameter. Grift et al. [12] showed that the friction coefficient can be measured using a single radial velocity measurement of particle at a distance of 4 m from the edge of the disk. The data showed that larger particles attained slightly higher velocities than did smaller ones. Kemp [13] replaced the existing theoretical models and correlations for particle motion with the new formulae and concluded that it is more suitable for initial design process in the cascading rotary dryers. Villete et al. [14] demonstrated that every velocity component can be deduced from the horizontal outlet angle measurement and the rotational speed. The study also led to establishment of a theoretical relationship between horizontal and vertical outlet angles. Butikov [15] analyzed spinning symmetrical top in which the forced precession is developed to visualize and better understand on a qualitative level a somewhat counter intuitive behavior of a gyroscope including precession under the force of gravity and nutation.

2. Theory and analytical models

The process of granulation is a size enlargement technique in which very fine particles are gathered into larger aggregates of particles ranging from 1.0 to 8.0 mm. In this technique, the binder (water) is added to the dry powder and the liquid films developed by the addition of binder cause the particle to adhere with each other. This process leads to the formation of aggregates and growth of granules. The formation of agglomerates and growth of granules can be described by two mechanisms viz. nucleation of particles and coalescence between agglomerates [16] as shown in Fig. 1.

The dynamics of granular systems are ubiquitous in nature and technology, yet they are still inadequately understood. But this new sago sizing mechanism effectively explains the dynamics of granular systems. The centrifugal flow analysis of spherical particle dynamics is generally done considering the components of two types of motions viz. rolling and sliding [9] and here the bouncing is also added. This simple granulator mechanism as shown in Fig. 2 consists of bowl, rod, gear mechanism, motors, sensors and control unit.

The bowl and rod are connected with the gear setup and motors which provide the spin and precession rotation. The bowl, rod and particle motions are examined and controlled by control unit through the sensors. The sago powder particles are granulated in a bowl which rotates with two different speeds viz. bowl spinning about its own center axis and the precession of the rod about vertical axis. The direction of rotation of the bowl and rod can be changed. The angle of inclination of

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