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Parameter estimation for porang (*Amorphophallus muelleri* Blume) chips milling by using a batch type of ball mills

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Abstract. Porang bulbs (*Amorphophallus muelleri* Blume) are native Indonesian bulbs which have high glucomannan content. It is almost similar to konjac bulbs (*Amorphophallus konjac*) which also glucomannan source. Porang flour is made from dried porang chips with about 10 % wet based water content. Unfortunately, there are no studies which were focused on the underlying mechanism of porang chip milling by using a batch type of ball mills. The objective of this research is to determine optimal milling rotational velocity and milling parameters of the kinetic model of porang chip milling by using ball mills. A batch type of ball mills was occupied in this research for milling 1.5 kg of dried porang chips. Optimal rotational velocity was calculated in order to have an optimal performance of milling. Kinetic model form of the back-calculation algorithm was chosen to describe the milling process. There were five estimated parameters of the validated kinetic model of the porang chip milling process.

Keywords: glucomannan, porang milling, ball mills

1. Introduction

The Glucomannan powder is usually imported from China which originated from konjac flour [1, 2]. Glucomannan powder is commonly used for food industrial ingredient for jelly, health, and pharmaceutical industries [3-5]. In East Java province, Indonesia, porang bulbs (*Amorphophallus muelleri* Blume) were mostly cultivated due to its glucomannan content. In order to extract glucomannan content, porang bulbs were sliced and dried and then processed into porang flour. Porang flour with a high content of glucomannan needs to be purified before it is used in industries because of the existence of calcium oxalate and other impurities [6, 7]. The accumulation of calcium oxalate in porang flour can cause itchy to skin and kidney stone if it is consumed [8, 9]. Physically, the porang chip was hard due to the presence of glucomannan, thus several studies of porang chip milling were conducted. A stamp mill was used to get porang flour but this method was time-consuming (8 to 10 hours spent for milling) and give small production capacity [10, 11]. Another method that used for porang milling was by using ball mills. It can produce 1.5 kg of porang flour in 4 hours [12]. This method occupies balls in order to make porang chip crushed into coarse and fine particles. Ball mills are mainly used for mineral grinding such as quartz, mining industries, cement production and mechanical alloying [13, 14].



Some mathematical models of ball mills grinding were developed. Kinetic models were built based on mass balance equations expressing the quantity of certain particle size interval, while energy models based on energy balance equation model [14]. Wet and dry ball mills grinding operation were also considered to gain fine particles productivity effect [13]. In energy model form, a numerical approach of Discrete Element Method (DEM) was used to study of ball mills energy requirements based on its physical design [15]. While in the kinetic model form, a back calculation algorithm was recommended to get breakage parameters for batch grinding [16]. Another solution for ball mills batch grinding model was also suggested in cumulative size distribution in the form of matrix notation [17]. Unfortunately, there are no studies which were focused on the underlying mechanism of porang chip milling by using a batch type of ball mills. Therefore, the objective of this research is to determine optimal milling rotation velocity and milling parameters of the kinetic model of porang chip milling by using a batch type of ball mills.

2. Materials and methods

A 1.5 kg dried porang chip with 10.09 ± 0.12 % wet based water content was used in this research. Porang chip was processed from porang bulbs originated from Madiun, East Java, Indonesia. The bulbs then washed, sliced in 5 ± 0.2 mm thickness, dried under the sun for 6 hours, and then moved to electrical oven for 8 hours.

A batch type of ball mills with 25 cm in diameter and 30 cm in length was used. The rotation of ball mills was achieved from 2 HP electric motor and regulated by using Toshiba inverter VF-S11. The inside of ball mills body was equipped with 3 lifters in 120° and 1 cm in height. It was filled with 3 sizes of stainless steel balls with a diameter 4.5 cm: 3.6 cm: 2.4 cm with a ratio of 4:2:1. While the mass ratio of chip to balls was 1:10 and occupied 25% of total ball mills volume.

The optimal rotation for ball mills was set at 65-80% from critical rotational velocity [18] or at 70-80% from critical rotational velocity [19]. Equation 1 was used for critical rotational velocity calculation. The balls and chips trajectory were captured by using 10.1 MP Sony camera DSC-S3000.

$$N = \frac{42,3}{D^{\frac{1}{2}}} \quad (1)$$

Where,

N = Critical rotational velocity (rpm)

D = Cylinder diameter (m)

The mathematical modeling was conducted by using a personal computer with a technical specification of processor Intel® Core™2 Duo CPU E7500 @ 2.93GHz, RAM 1980MB, VGA onboard Intel® G41 Express Chipset 1024MB, and 300GB hard disk. For programming software, MATLAB® R2007b was occupied under Microsoft Windows XP professional operating system. The particle diameter size observed was less than 500 μm by using particle size distribution by using CILAS 1090-dry. The mathematical model used in this research was based on back-calculation algorithm ball mills grinding [16] as written in Equation 2.

$$\frac{\partial F(x,t)}{\partial t} = \int_x^\infty S(x')B(x,x')dF(x',t) \quad (2)$$

The discretization of Equation 2 was written in Equation 3 with total fraction size was divided into N grids.

$$\frac{\partial F_i}{\partial t} = \sum_{j=i+1}^N S(x_j)B(x_i,x_j)(F_j - F_{j-1}) \quad (3)$$

where:

F_i : Cumulative size fraction of particle less than or equal to x_i

$S(x_j)$: Selection function

$B(x_i, x_j)$: Breakage function: Cumulative distribution of particle size less or equal to the i^{th}

x_i : The particle diameter of fraction i

The selection and breakage function were consecutively written in Equation 4 and Equation 5.

$$S_j = a \left(\frac{x_j}{x_m} \right)^\alpha \quad (4)$$

$$B_{i,j} = \phi \left(\frac{x_i}{x_j} \right)^\gamma + (1-\phi) \left(\frac{x_i}{x_j} \right)^\delta \quad (5)$$

The parameters associated with selection function were a and α , while parameters associated with breakage function were δ , γ , ϕ .

The matrix form of Equation 3 was given:

$$\frac{d\tilde{F}}{dt} = \tilde{A}\tilde{F} + \tilde{C} \quad (6)$$

$$A_{i,j} = \begin{cases} S_j B_{i,j} - S_{j+1} B_{i,j+1} & ; i < j \\ -S_{j+1} B_{i,j+1} & ; i = j \\ 0 & ; i > j \end{cases} \text{ and } C_{i,1} = S_N B_{i,N} \quad (7)$$

The differential equations were solved by using Runge-Kutta formulation with Dorman-Prince method as the default method in MATLAB called ODE45. Parameter estimation was conducted by using the sum of squared error optimization between predicted from a mathematical model and observed from measurement data. This approach was conducted by using the *lsqnonlin* function in MATLAB. Whereas, the confidential interval calculated from estimated parameters were obtained by *nlparci* function.

3. Results and discussion

The critical rotational velocity calculation of the ball mills with 25 cm diameter was based on Equation 1 resulted in 84.6 rpm. While the calculation of optimal rotational velocity for the ball mills (70% from the critical rotational velocity) was 59.22 rpm which was rounded into 60 rpm.

Furthermore, this optimal value was validated by using a camera. The balls and flour trajectories were captured inside the 60 rpm rotating ball mills body as served in Table 1. It was observed that the optimal condition of milling had reached. Inside the ball mills body, both the compressive and friction forces occurred during the milling. The slower the rotation velocity, the friction forces was more dominant than the compressive forces. This condition made the milling process last longer and the milling temperature increase. However, by making the rotational velocity faster than optimal rotational value could not increase those forces value because the centrifugal forces will more dominant than compressive and friction forces. The centrifugal forces will make the balls and the flour revolve at the wall of ball mills body and minimum compressive and friction forces occurred during the milling process.

The chips milling was observed for 3 hours and the flour particle size distribution data was measured every hour by CILAS 1090-dry particle size analyzer. The total of 100 data point measurement was ranging from 0.1 μm to 500 μm was then compared to the mathematical model results to obtain the five milling parameters. The simulation and the parameter estimation occupied the mathematical model with a back-calculation algorithm which cumulatively taken into account the particle distribution ranging from fine particle fraction at the first grid (0.1 μm) to coarse particle fraction at the N^{th} grid (500 μm). Therefore, the last grid value should be equal to 100% or 1. The initial parameters guess was obtained by studying the parameters effect on the model simulation. The best parameters guess which resulted in the nearest simulation value to the measurements data were chosen as the initial parameter guess for

optimization. The initial parameter guess was consecutively a ; α ; δ ; γ ; $\phi = 1.4$; 0.5 ; 1000 ; 1.15 ; and 1.0 . The simulation and the parameter estimation result were served in Figure 1.

Table 1. The trajectories in ball mills chamber.

The optimal rotational velocity (rpm)	Loading condition	
	Stainless steel balls	Stainless steel balls and porang flour
60		

In Figure 1, there are two types of milling simulation figures which describe the same numbers which are: the top figure with logarithmic scale axis and the bottom figure with regular scale axis. The logarithmic axis described equal distance for measurement data from fine to coarse particles fractions. While the regular axis cannot describe the fine particle fractions clearly. In Figure 1, the logarithmic scale part described that at the fine fraction the model simulation hardly fit the measurements data. The unique trajectories of measurement data points especially at the fine fraction were due to the effect of three sizes of ball diameter which characterize the milling. Each size of the ball had a certain contribution on the certain range of particle fraction appearance. The balls with a diameter of 4.5 cm contributed on mainly $330\text{ }\mu\text{m}$ - $460\text{ }\mu\text{m}$ particle size appearance, the balls with a diameter of 3.6 cm contributed on mainly $100\text{ }\mu\text{m}$ - $150\text{ }\mu\text{m}$ particle size appearance, and the balls with a diameter of 2.4 cm contributed on mainly $30\text{ }\mu\text{m}$ - $40\text{ }\mu\text{m}$ particle size appearance.

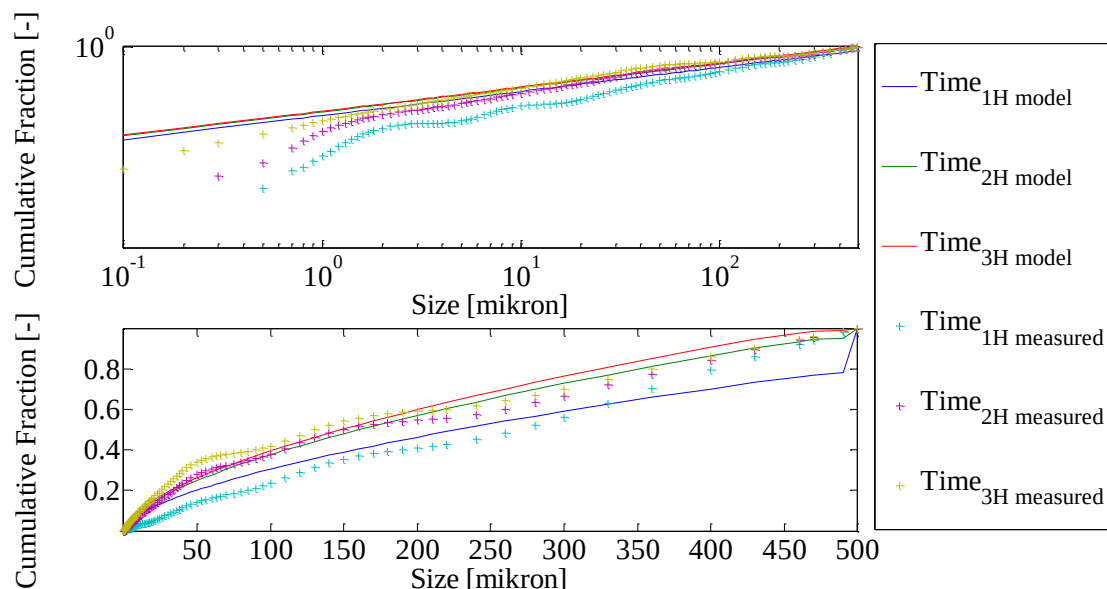


Figure 1. The measurement values and model simulation of cumulative size distribution during milling

While in Table 2, the estimated parameters and its confidential interval were served. The α and γ parameters had precisely estimated while a , δ , and ϕ parameters had less precision values due to higher values of deviation. The highly strong correlation among parameters might influence the estimation

process. Moreover, the sensitivity of a , δ , and ϕ parameters were high due to their correlation. These parameters represent the influence of the quantity of the balls, the ratio of balls diameter, ball mills rotational velocity, flour to ball mass ratio, and the effective volume of the milling chamber for particle breakage mechanism.

Table 2. Estimated parameter values.

Parameters	Estimated values	Confidential intervals ($\times 10^6$)	
a	1.4	-1.3291	1.3291
α	33.4	0.0000	0.0001
δ	1000	-5.4291	5.4311
γ	0.6	0.0000	0.0000
ϕ	1.1	-0.9753	0.9753

The average diameter of measurement data compared to the simulation results can be seen in Figure 3. The difference error percentage at 1 hour, 2 hours, 3 hours of milling were 0.75 %, 4.32 %, 3.51% where all the error percentages were below 5%, and even below 1% for the first hour. Thus, the estimated parameters used for the ball mills simulation was very close to the average particle diameter of the measurement data obtained.

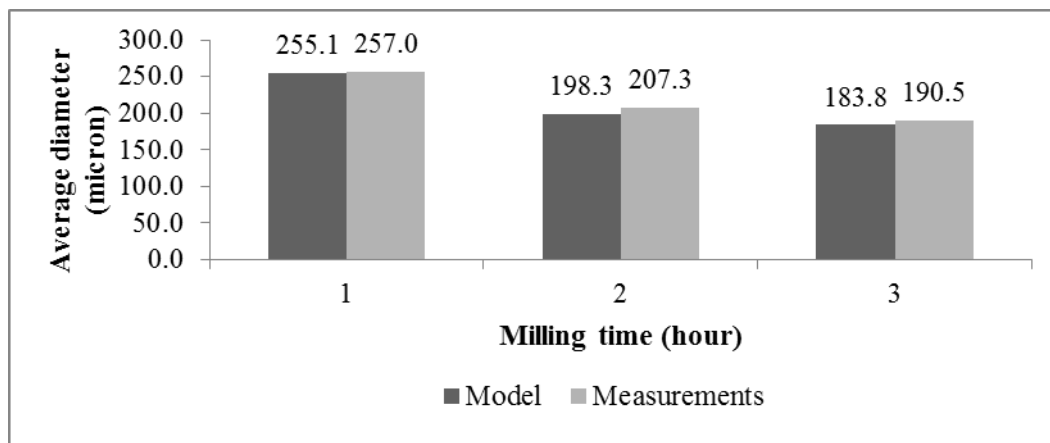


Figure 2. Model simulation and measurement average diameter

4. Conclusions

The milling process was conducted at the optimal condition with the optimal rotational velocity of 60 rpm. The estimation of breakage parameters was successfully conducted by using a back-calculation algorithm model and can describe the breakage mechanism during porang milling with estimated parameters a ; α ; δ ; γ ; ϕ = 1.4; 33.4; 1000; 0.6; and 1.1.

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