International Journal of Scientific Engineering and Technology (ISSN : 2277-1581)
Volume No.4 Issue No.2, pp : 36-39 01 Feb. 2015

Assessment and Optimization of Bulk Density and Angle of Repose of Tea Leaves for Metering Device Using Desirability Function

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Abstract:The current research focuses on the estimation of bulk density and angle of repose of tea leaves at different moisture content and size and development of a mathematical model for bulk density and angle of repose using response surface methodology followed by numerical optimization of responses using desirability functions. Further work was done on the design optimization of feed hopper and metering system with bulk density and angle of repose. In tea processing, during withering and maceration process the whole leaves are subjected to size reduction, rolling, maceration, feeding and conveyance. The tea leaves are generally not uniform due to plucking standard, moisture content of the leaf and the variety. Non-uniformity in feed rate of tea leaves which will ultimately pass through the feed hopper will not only affect the cut size of the leaves but unwanted friction between CTC machine rollers will cause rise in temperature to about 60˚C which will ultimately affect the quality of tea by influencing its theaflavin/thearubigin (TF/TR) ratio. Practically, rise in temperature above 35˚C deteoriates the quality of leaf and non-uniformity in leaf cutting will affect granule formation. Bulk density and angle of repose are important physical parameters of tea leave for free flow behavior during processing. Response surface methodology was used to examine the effect of size of cut leaf and moisture content of tea leaves on the mean bulk density and mean slide angle of repose.

Keywords: Tea processing, Angle of repose, Bulk density, Response surface methodology, Desirability function, Withering, Moisture content.

I. INTRODUCTION:

Tea is the most popular beverage worldwide. Processing of CTC black teas is really a complex biochemical process where the fresh harvested leaf undergoes numerous processing steps of withering, maceration, fermentation, drying and grading. During withering process the moisture content of tea leaf which varies from 83 to 70 percent which affects the final quality of tea [1]. In CTC tea industry, tea leaves are cut into fine particles using the CTC machine where the whole leaves are subjected to size reduction, rolling, maceration, feeding and conveyance [2]. The size of tea leaves ranges from 10 mm to 75 mm and after maceration it reduces to less than 0.1 mm size. Non-uniformity in feed rate of tea leaves which will ultimately pass through the feed hopper and then through shifter, precut and cut devices will not only affect the cut size of the leaves but unwanted friction between rollers will cause rise in temperature to about 60˚C which will ultimately affect the quality of tea by influencing its theaflavin/thearubigin (TF/TR) ratio [3]. Practically, rise in temperature above 35˚C deteoriates the quality of leaf and non-uniformity in leaf cutting will affect granule formation [4]. The performance of the movement of tea leaves through feed hopper depends on a number of factors like Throughput rate, length of travel, change in elevation and nature of material like size, bulk density, angle of repose, abrasive, corrosive and wet or dry condition [5,6,7,8,9,10,11,12]. Moisture variance may give complexity in metering of flow rate of leaf in intervening time of processing. Earlier researches have shown that moisture and temperature has affect on withering which finally affects catechin degradation, formation of theaflavins (TF), thearubigins (TR) and volatile flavor compounds (VFC) [13, 14]. Excess moisture stress during withering promotes the generation of reactive oxygen species (ROS) which damages the lipoprotein membrane and involves loss of catechins by process of oxidation. TFs and TRs contribute to brightness, briskness of black tea liquor and taste, tone, strength of the brew respectively. Withering decreases protein content, reduction in polyphenoloxidase (PPO) activity; lipid degradation occurs by about 20% during withering. Proper control of temperature is an important factor in getting good quality of tea since high temperature during fermentation lowers the quality and excessive high temperature during withering gives rise to uncontrolled fermentation like reactions.

Bulk density and angle of repose are important physical parameters of tea leave for free flow behavior during processing. These two parameters may be affected with respect to degree of withering and size of tea leaf. The bulk density of leaf also varies due to plucking standard, tea clone and moisture content. Angle of repose is the angle at which tea leaves will rest on a pile and indicates about the behavior of the internal friction of the tea leaves. Bulk density and angle of repose are useful characters for determining the capacity of withering troughs and bins and also performance characteristics of conveyors such as screw or belt type. Further, high variation in angle of repose of tea leaves may bring differential internal friction, higher angle means higher internal friction and vice versa. This character decides the power requirement of the conveyor system. Non-uniformity in feed rate and leaf cut size will ultimately affect the temperature of tea processing, thus affecting its quality. The determination of bulk density and angle of repose for proper monitoring of cut sizes of tea leaves with desirability function is novel to the best of our knowledge.

II. MATERIALS AND METHODOLOGY

2.1. Sample preparation

The research material, tea clone of TV25 variety grown in IIT Kharagpur, was harvested manually and transported to the experimental site avoiding overloading; cut manually across the length by using knife at five levels i.e. 10, 16, 30, 44 and 50 mm as shown in Fig. 1. Further, the cut leaves were subjected to withering and the moisture content of each cut sample was measured at a regular interval of 30 min with the help of Halogen Moisture Meter (Model HB43-S).

Fig. 1: Cut tea leaves of different sizes used for study on bulk density and slide angle of repose.

2.2. Determination of fineness of tea leaves

Bulk leaf is considered as fine plucking when about 75% of the plucked leaf is two leaves and a bud. The average of tea leaf fineness was calculated.

2.3. Determination of bulk density

A wooden cube box of uniform inner dimensions of 100 mm was considered for measurement of bulk density of tea leaves. The leaves were completely filled in the space and weighed. The density of the tea leaves were calculated with the following formula:

$$\text{Bulk density, Kg/m}^3 = \frac{\text{Weight of the leaves, kg}}{\text{Volume of the box, m}^3} \quad \ldots(1)$$

2.4. Measurement methods of slide angle of repose

The sliding angle of repose of tea leaves was determined by using a movable inclined metal plane box of dimensions 150mm x 100mm x 50 mm. in length, width and depth respectively. For measurement of angle of repose at different interval in the study period the leaves were filled up in the box and leveled by a scale so that box holds full volume of leaves. Thereafter, the box was gradually lifted upwards till the leaves starts sliding down. The angle made by the inclined plane to the horizontal surface at which the leaves start sliding was determined as the sliding angle of repose. The angle of repose can also be measured by calculating the distance between pivot point to end of the box and height of the end point of the box with the horizontal surface as done by literature methods [15].

$$\alpha^0 = \frac{180}{\pi} \times \sin^{-1}\left(\frac{h}{L}\right) \quad \ldots(2)$$

where, α is angle of repose in degree, h is vertical height between end point of base plate container to center pivot point in mm and L is distance between end point of base plate container and center of pivot point in mm.

2.6. Mathematical modeling

Response surface methodology (RSM) was used to quantify the relationship between measured responses (mean bulk density and mean slide angle of repose) and the input parameters (moisture content and size of leaf). The objective was to find out a desirable location in design space (maximum, minimum or an area of interest) where the response is stable over a range of parameters. Central Composite Design (CCD) was selected under the response surface methodology as it is insensitive to missing data and replicated center points which provide outstanding prediction capacity near the centre of the design space. A CCD has three groups of design points, (a) two-level factorial or fractional factorial design points, (b) axial points (c) centre points [16].

Responses (bulk density and slide angle of repose) assumed as a polynomial of independent factors (moisture content and size of tea leaves), their interactions and coefficients of the polynomial are calibrated by regression analysis of experimental data. Analysis of variance (ANOVA) and Coefficient of determination (R^2) were used for the validation of the outcome model. Design expert® V7 software was used for the mathematical modeling and validation diagnostics.

3. RESULT AND DISCUSSION

3.1. Influence of moisture content, particle size of tea leaves (cut) and their interaction on the bulk density

The result shows the quadratic is best fit model with a p-value 0.0309. Eq.(3) shows the general form of the quadratic model which shows the relationship and the equation describes the change of bulk density of tea leaf with respect to changes in moisture content as well as tea leaf size which changes with coded values.

$$Y_1 = a_0 + a_1 A + a_2 B + a_3 AB + a_4 A^2 + a_5 B^2 \quad \ldots(3)$$

Where, $Y_1 =$ mean bulk density of tea leaves, kg/m^3, $a_i =$ model coefficients, where i=0, 1, 2, 3, 4 and 5, A= moisture content of tea leaf, % and B = size of tea leaf, mm.

ANOVA analysis showed that model terms (A, B, AB, A^2) which are significant except B^2 term. Thus the model was changed to Eq. (4). The model equation with actual coefiicent is given in Eq. (5).

$$Y_1 = a_0 + a_1 A + a_2 B + a_3 AB + a_4 A^2 \quad \ldots(4)$$

$$Y_1 = -2450 + 78.4A - 8.24B - 0.1AB - 0.59A^2 \quad \ldots(5)$$

The effect of moisture content and size of tea leaf and their interaction effect on mean bulk density is displayed in 3D-surface shown in Fig.2 (a).

The result showed that the "Lack of Fit F-value" was not significant. Based on the insignificant result of lack of fit value there is a scope to change the model. Normal probability plot showed that the residuals are following a normal distribution. A graph of the actual response values versus the predicted response values showed the group of values which are not easily predicted by the model.

Bulk density of tea leaves varies with size of tea leaves. The results showed that mean bulk density was inceased with decrease in size of tea leaves from 65.50 kg/m^3 to 124.15 kg/m^3.

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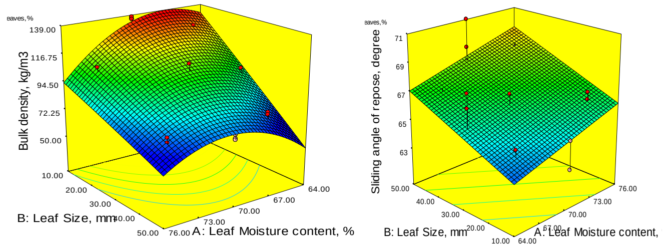
At initial stage of withering, mean bulk density of tea leaves was increased with decrease in moisture content till it attain 70 percent. Thereafter, the bulk density was again decreased. This was due to initial change in leaf from elastic to plastic stage and becomes leathery. Thereafter, loss in moisture continued while the volume of leaf was least disturbed.



(a) *(b)*

Fig. 2. 3D-surface graph for effect of moisture content and tea leaf size on the average size of mean bulk density and mean slide angle of repose for tea leaves

3.2. Influence of moisture content, particle size of tea leaves (cut) and their interaction on the sliding angle of repose

From the analysis, the linear model was found best one to express the angle of repose as a function of moisture content and tea leaf size.

The general form of the model as Eq. (6) was considered to describe the angle of repose.

$$Y_2 = a_0 + a_1 A + a_2 B + a_3 AB + a_4 A^2 + a_5 B^2 \qquad \ldots(6)$$

Where, $Y_2 =$ Mean angle of repose for tea leaves, Degree, $a_i =$ Model coefficients, where i=0, 1, 2, 3, 4 and 5, A= moisture content of tea leaf, % and B = size of tea leaf, mm.

Model and model terms (A, B) are significant. Thus model was changed to Eq. (7) and Eq. (8).

$$Y_2 = a_0 + a_1 A + a_2 B \qquad \ldots(7)$$

$$Y_2 = 49.90 + 0.20A + 0.08B \qquad \ldots(8)$$

The effect of moisture content of leaf and leaf size and their interaction on mean slide angle of repose is displayed in 3D-surface graph as shown in Fig. 2 (b). The "Lack of Fit F-value" 5.62 implies that the Lack of Fit is significant. Significant result of lack of fit showed that there is no further scope to fit the model. Proposed model was evaluated through Analysis of Variance (ANOVA) and coefficient of determination (R^2) while normal probabilty and actual vs predicted plot were used to diagnose the residuals and predicted values for the model. Normal probability plot showed that the residuals are following a normal distribution. The result showed that the angle of repose was found to be higher with increase in moisture content and leaf size. Maximum slide angle of repose was observed when size of the leaf was more than 50 mm and moisture content was 76 percent or more. Higher value of slide angle of repose indicates the character of non free flowing leaf with sluggish nature.

3.3. Numerical optimization of the responses for operation of tea leaves from withering to pre-cutting process

Numerical optimization was done for bulk density and slide angle of repose of tea leaves using desirability function and further optimized to find an acceptable set of conditions that will meet all the defined goals but not to get to a desirability value i.e. 1.0. The simultaneous objective function is a geometric mean of all transformed responses as followed-

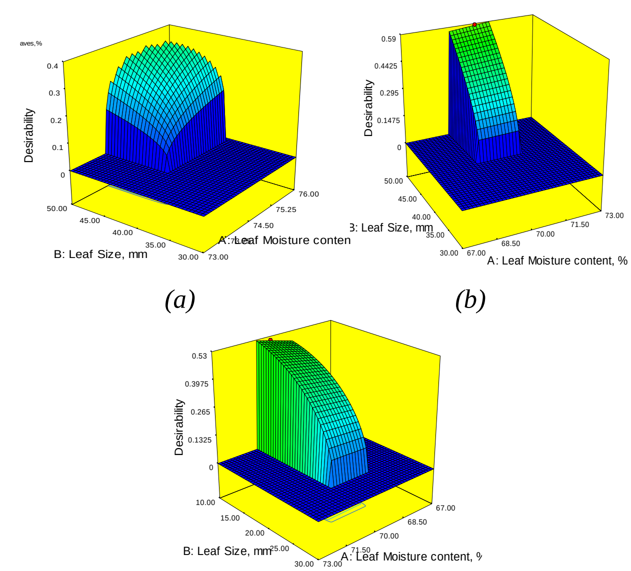
$$D = \left(d_1 \times d_2 \times d_3 \times \ldots\ldots \times d_{n-1}\right)^{\frac{1}{n}} = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}} \qquad \ldots(9)$$

Where, D is the desirability, d is the response and n is the number of responses in the measure [16].

The leaf handling process starting from harvesting to endpoint of size reduction, under goes various modes of handling i.e. harvesting, loading, transportation, unloading, feeding in conveyance system to withering trough and withering to precut device. During these steps of operation, the bulk density of leaf changes due to moisture loss, structure of the leaf, leaf elasticity and plasticity. Considering these changes, the container and other structural design like storage container size, shape and inclination of conveyor belt, size of withering trough and metering device for size reduction of leaf are necessary.

Based on the above steps of tea leaf handling from field to factory, the present study is considered which are as follows-

Case 1. *Movement of harvested leaf from field to end point of withering (Moisture content of leaf, A >74% (wb) and Size of the leaf, B >50 mm),* ***Case 2.*** *Conveyance of leaf from end point of withering to precut unit (Moisture content of leaf, 69<A<71% (wb) and Size of the leaf, B > 40 mm),* ***Case 3.*** *Feeding of leaf in precut device (Moisture content of leaf, 69<A<71% (wb) and Size of the leaf, B< 25 mm)*



(a) *(b)*

(c)

Fig. 3. Numerical optimization of mean bulk density and mean slide angle of repose for tea leaves

From the above mentioned solutions as shown in Fig.3(a), for 75 percent moisture content and 46 mm size of leaf in Case 1, the bulk density and slide angle of repose were 69.33 kg/m^3 and 69.07 degree respectively. In this case bulk density is more important parameter than the slide angle of repose. It can be revealed that the size of the box for harvesting and transportation should be designed such that leaf should not be compressed and should be free from excessive pressure caused by self weight for good aeration. If proper aeration is not provided leaves may damage due to heat released through exothermic reaction within the tea leaf. In this stage leaf temperature should not be exceed 35^0C as recommended by Tea Research Association, Tocklai, Jorhat, India.

Considering Case-2 as shown in Fig.3 (b), from the above mentioned solutions, for 70 percent moisture content and 55 mm size of leaf, the bulk density and slide angle of repose are 69.33 kg/m^3 and 68.99 degree respectively. In this case both bulk density and slide angle of repose are important for the free flow of the material during conveyance and metering.

In Case 3 as shown in Fig.3(c), for 70 percent moisture content and 10 mm size of leaf, the bulk density and slide angle of repose are 130.84 kg/m^3 and 65.24 degree respectively. This indicates that after pre-cutting of leaf the bulk density of the leaf increases while slide angle of repose decreases.

4. CONCLUSIONS

RSM was used to examine the effect of size of cut leaf and moisture content of tea leaves on the mean bulk density and mean slide angle of repose. Equations have been proposed to express mean bulk density and mean slide angle of repose in accordance with size and moisture content of leaf. It has been found that bulk density varies with change in moisture content and leaf size. This study not only relates bulk density and slide angle of repose to tea leaf physical properties but also make it possible to consider the character of the system to consider them in the design of the metering, conveying and storage system for green tea leaf. Solutions proposed may be useful in design of these systems with the help of numerical optimization using desirability function.

Acknowledgements

The work reported here was carried out as part of a collaborative project between IIT Kharagpur and Tea Board of India at Tea Engineering Research Centre, Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur, India.

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