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EFFECT OF CHUTE LEVEL
ON MILL CAPACITY

By

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**KEYWORDS: Chute, Mill,
Capacity, Level, Model, Control.**

Abstract

IN MANY FACTORIES, the feed chute of the first mill is operated with a high chute level for the purpose of maximising the cane rate through the mill. There is a trend towards trying to control chute level within a small control range near the top of a chute that can result in rapid changes in cane feeding rate to maintain the chute level set point. This paper reviews the theory that predicts higher cane rate with higher chute level and discusses the main weakness in the theory that it does not consider the beneficial effect on capacity of cane falling from the top of the chute to the top surface of the cane mat. An extension to the chute theory model is described that predicts higher capacity with lower chute level because of the effect of the falling cane. The original model and this extended model are believed to be the upper and lower limits to the true effect. The paper reports an experiment that measured the real effect of chute level on capacity and finds that increasing chute level does lead to higher capacity but that the trend is only about one-third as strong as the original theory predicted. The paper questions whether the benefits of slightly greater capacity outweigh the costs of operating with the small control range near the top of the chute.

Introduction

Since being described by Donnelly (1958), the closed feed chute has become a feature of virtually all milling unit designs as a means of increasing mill capacity. Feed chutes are now vertical or near vertical and generally about 3 m in length.

The maintenance of a set level of bagasse in the feed chute in many milling units is the key parameter that defines the rate through (Maclean *et al*., 1977) or speed of (Nielsen and McEachran, 1975) the milling unit.

In many factories, particular attention is paid to the feed chute of the first mill, since this mill is typically the rate-setting item of plant for a factory. It is common to see first mill feed chutes taller than the chutes for the rest of the milling train.

It is also common to see first mill feed chutes operated with a higher chute level than other mills. It is widely accepted that high chute levels lead to high throughput (Murry and Hutchinson, 1958).

Some factories have now taken chute level control of first mills further and are only measuring (and hence controlling) chute level over a small section of the feed chute near the top (Figure 1) in an effort to ensure the chute remains full.

To maintain the level within a small section of the chute requires fast acting control. Fast acting control is also required to ensure the chute does not over-fill from having a level set point near the top of the chute.

Fig. 1—Level sensors only in the top part of the chute.

To improve control when chute level is only allowed to vary over a narrow range, some factories have implemented *cane carrier level* control to maintain a more consistent feed to the first mill (Figure 2).

Fig. 2—Carrier level sensors.

This paper examines the benefits of operating with a high level of prepared cane in the feed chute of the first mill in terms of capacity and considers whether those benefits justify the extra complexity that is necessary to maintain good level control with a full feed chute.

Why it is believed that high chute levels result in high capacity

The basic equation for determining mill capacity per unit length of roll (q_c) was presented by Murry (1960):

$$q_c = \rho_\alpha h_\alpha S \cos\alpha \qquad (1)$$

where ρ_α is the bulk density of the cane at the mill entry, h_α is the chute setting at the mill entry, S is the roll surface speed and α is the contact angle. The chute setting and contact angle can be controlled through settings and the surface speed is determined by the drive controls.

According to equation (1), for given settings and speed, the bulk density of the cane is the only remaining factor that affects capacity. If bulk density can be made higher, the mill capacity can be increased.

For a milling unit with a closed feed chute, the mill entry is located at the bottom of the feed chute. The bulk density of the prepared cane at the bottom of the feed chute can be increased by increasing the pressure on the prepared cane at the bottom of the feed chute. There is a well defined relationship between bulk density and pressure (Murry, 1998).

Murry and Hutchinson (1958) presented a theory to estimate the pressure on the prepared cane at the bottom of the feed chute. The theory divided the prepared cane in the chute into a series of elemental strips through the cross-sectional area of the chute as shown in Figure 3.

A force balance on each elemental strip consisted of the pressure on the strip from the prepared cane above it (p), the weight of the strip itself (dW), the normal force exerted from the side walls of the chute in response to the pressure on the strip (R) and the frictional force (F) associated with that normal force.

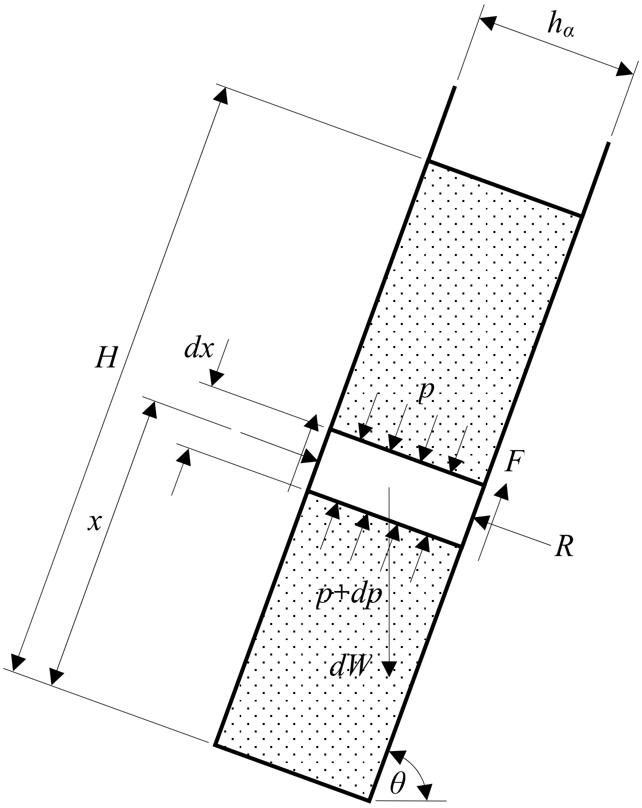

Fig. 3—Chute model (Murry and Hutchinson, 1958).

The force balance for the strip in the direction along the chute can be simplified to:

$$dp = \left[g\left(\sin\theta - \mu\cos\theta\right)\rho - \frac{2\mu k}{h_\alpha} p \right] dx \qquad (2)$$

where g is the acceleration due to gravity, ρ is the prepared cane density (dependent on the pressure p), μ is the coefficient of friction between the prepared cane and the chute walls and k is the ratio of transverse pressure to axial pressure in the chute. The equation can be solved by integrating from $x = H$ (the height of the prepared cane in the chute) to $x = 0$ (the bottom of the chute). The pressure $p = 0$ when $x = H$. The density ρ can be calculated from the pressure p using a constitutive equation such as presented by Murry (1998).

To illustrate the relationship defined by equation (2), Figure 4 shows a curve generated using chute width h_α = 500 mm, chute angle θ = 90°, coefficient of friction μ = 0.3 and ratio of transverse pressure to axial pressure k = 0.37. The prepared cane properties relating the pressure p to the density ρ were based on those of the P_1 preparation level reported by Murry (1998, Table 2), assuming a cane fibre content of 13%, density of fibre of 1530 kg/m^3 and density of juice of 1080 kg/m^3. Figure 4 shows the density of cane at the bottom of the feed chute increasing from 394 kg/m^3 at a chute level of 1 m to 451 kg/m^3 at a chute level of 3 m, an increase of 14%. Figure 4 also shows that the effect of increasing chute level on the density reduces as the chute level increases. If the chute level was increased a further 2 m, the increase in density would be only an additional 5%.

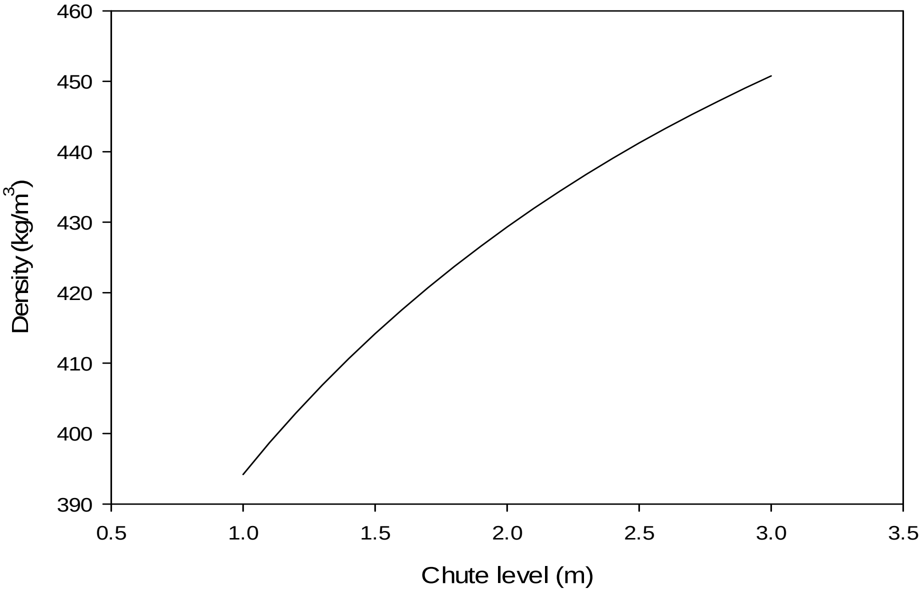

Fig. 4—Relationship between chute level and density at the bottom of the feed chute using the Murry and Hutchinson (1958) model.

Variations of equation (2) and variations of Figure 4 have been published widely and, along with observations by milling personnel, are believed to be the basis of the belief that high chute levels cause high capacity.

Extensions to chute theory

Figure 5 shows two chutes with identical chute levels. Chute (a) is a short chute while chute (b) is a tall chute. If asked which chute will have the highest density at the bottom of the chute, most technologists would select chute (b), the reason being that the prepared cane that drops into the tall chute will hit the top of the prepared cane mat and the impact will cause the mat to compress. The Murry and Hutchinson (1958) theory, however, predicts that the density in both chutes will be the same.

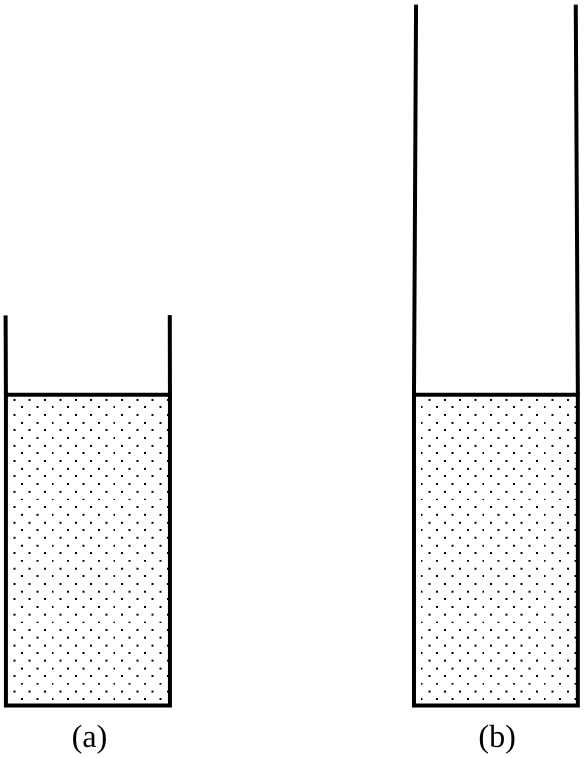

Fig. 5—Two chutes of the same level but with different heights

An extension was made to the chute model to account for the impact of the falling cane on the density at the bottom of the chute. As far as the model is concerned, this impact can be accounted for by starting the solution of equation (2) with a pressure p greater than zero at $x = H$. The difficulty lies in determining what that pressure should be.

To determine the size of the pressure, an energy balance was undertaken. When dealing with energy, it is convenient to deal with a constant mass of cane in the chute, rather than a constant volume (height) as per the formulation of equation (2). To convert equation (2) into a mass-based model, the following relationship was used to relate the mass of the strip (dm) to the height of the strip (dx):

$$dm = \rho L h_\alpha dx \qquad (3)$$

where L is the width of the chute. In addition, a simplification was made by assuming $\theta = 0$. Equation (2) then becomes:

$$dp = \frac{1}{Lh_\alpha}\left[g - \frac{2\mu k}{h_\alpha}\frac{p}{\rho}\right]dm \qquad (4)$$

The energy in the cane in the chute has been accounted for through three components:

- Kinetic energy (E_k)

- Strain energy (E_s)
- Frictional energy (E_f).

The kinetic energy in a strip is calculated from:

$$E_k = \frac{1}{2} dm\, v^2 \tag{5}$$

where dm is the mass of cane in the strip and v is the velocity of the strip.

The velocity v is calculated from:

$$v = \frac{dx}{dt} \tag{6}$$

where dt is the time to process the strip. The time can be determined from:

$$dt = \frac{dm}{\dot{m}} \tag{7}$$

where $\dot{m}$ is the cane rate.

The strain energy in the strip can be calculated from:

$$E_s = L h_\alpha \int p\, de \tag{8}$$

where e is the amount of compression of the strip, calculated from:

$$e = \left(\frac{\rho}{\rho_0} - 1 \right) dx \tag{9}$$

and ρ_0 is the density of the cane at zero pressure.

The frictional energy from the strip can be calculated from:

$$E_f = dF\ H \tag{10}$$

where dF, the frictional force from the strip can be calculated from:

$$dF = \mu L (2kp + \rho g h_\alpha \cos\theta) dx \tag{11}$$

The total energy in the chute is then:

$$E = \sum (E_k + E_s + E_f) \tag{12}$$

for all strips.

Because the cane in the chute is in a steady flow condition, in the time it takes to process one chute full of cane, another chute full of cane has entered the chute. This second chute full of cane has fallen from the top of the chute to the upper surface of the cane in the chute. The potential energy of this cane is:

$$E_p = mg(H_t - H)$$

(~~12~~13)

where m the total mass is calculated from:

$$m = \sum dm$$

(~~13~~14)

for all strips, H_t is the physical height of the chute and H is the chute level:

$$H = \sum dx$$

(~~14~~15)

for all strips.

If E_0 is the total energy in the chute when there is no pressure applied to the top surface and E is the total energy in the chute after application of the pressure that simulates the impact force of the falling cane, then to achieve an energy balance:

$$E = E_0 + E_p \qquad (\cancel{15}16)$$

The pressure on the top surface is selected to ensure that equation (~~15~~16) is satisfied.

Exploring the extended chute theory

To gain an impression of the relative importance of the kinetic, strain and frictional energy components, the chute described earlier was assessed with a 3 m chute level. The cane rate was chosen to be 500 t/h (139 kg/s) and the width of the chute was selected to be 2 m. The energy components calculated for this case are presented in Table 1. It is clear that the majority of the energy is lost through friction.

Table 1—Energy components for the cane in a 3 m tall chute

Energy component	Energy (kJ)
Kinetic energy	0.1
Strain energy	1.4
Frictional energy	14.9

To assess the effect of the extended theory on the predicted cane density at the bottom of the chute, the same chute was again modelled to compare against the original model data shown in Figure 4. For the extended model, the physical height of the chute was assumed to be 3 m so that lower chute levels lead to increased distances for the cane to drop onto the top of the cane mat.

Figure 6 compares the model predictions of the original Murry and Hutchinson (1958) model with those of the extended model. Most notably, the trend of density with chute level is reversed with the extended model predicting a greater benefit from the falling cane than from the formed mat of cane.

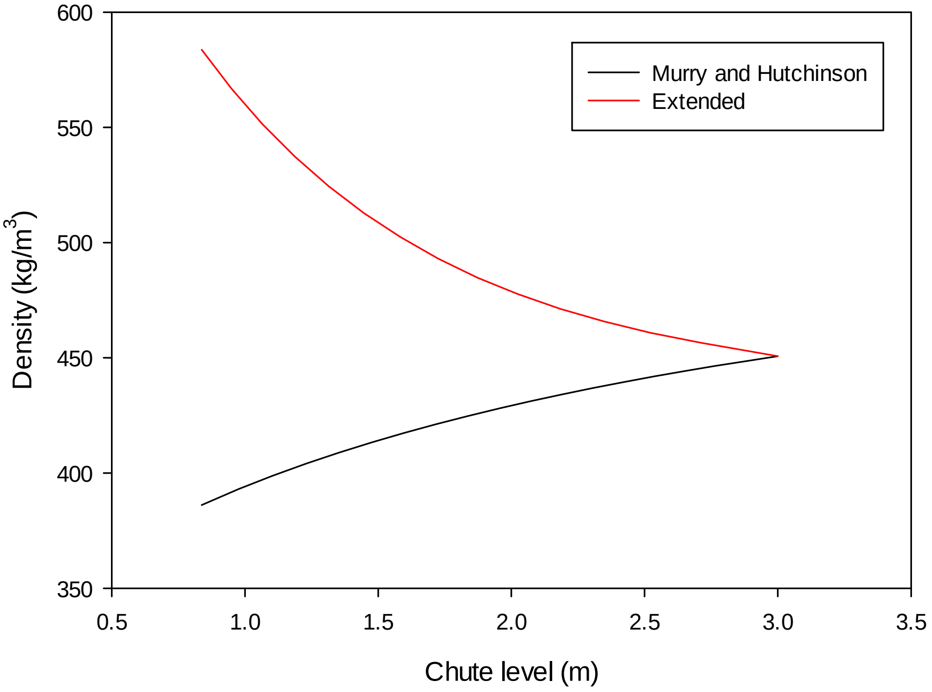

Fig. 6—Comparison of Murry and Hutchinson (1958) and extended model density predictions.

It is noted that the extended model assumes no energy loss in the falling cane. In reality, there will be some air resistance and perhaps some side wall friction that will reduce the effect of the falling cane, bringing the extended model prediction closer to the Murry and Hutchinson model prediction. The Murry and Hutchinson model prediction is considered to be a lower limit to the true density while the extended model prediction is considered to be an upper limit to the true density.

An experiment to test chute theory

To get a better appreciation of the effect of chute level on cane rate, an experiment was conducted at Tarumã factory in Brazil on their 78 inch milling train on 6 August 2010. The experiment assessed the effect of first mill chute level set point on cane rate. Six tests were conducted, three at a first mill chute level set point of 10% and the other three at a first mill chute level set point of 90%. The two set points corresponded to chute levels of 2.3 m and 3.1 m respectively.

Each test was conducted for one hour. During the one hour period, the control system recorded the first mill chute level (to check that the set point was achieved), the turbine speed (to ensure that mill speed did not affect the cane rate) and top roll lift (an indication of cane rate). In addition, the total tonnes of cane crushed during the test were recorded, along with the fibre content of each delivery that was sampled during the test.

The test details are presented in Table 2. The results are presented in Table 3.

Table 2—Chute level experiment test details.

Test	Start time	Chute level set point (%)
1	10:00	90
2	11:00	10
3	12:00	90
4	13:00	10
5	14:00	10
6	15:00	90

Table 3—Chute level experiment results.

Test	Chute level (%)	Turbine speed (r/min)	Roll lift drive side (mm)	Roll lift other side (mm)	Roll lift mean (mm)	Cane rate (t/h)	Fibre content (%)	Fibre rate (%)
1	54	5977	9.1	2.8	5.9	679	11.7	79.5
2	12	5966	11.6	3.6	7.6	589	12.3	72.4
3	62	6004	11.0	3.2	7.1	655	12.0	78.6
4	13	6031	10.1	2.5	6.3	655	12.1	79.5
5	10	6027	11.0	2.3	6.7	651	12.6	81.9
6	52	6012	13.2	4.3	8.8	610	12.6	76.8
Mean 10%	12	6008	10.9	2.8	6.9	632	12.3	77.9
Mean 90%	56	5998	11.1	3.4	7.3	648	12.1	78.3

As shown in Table 3, the mean chute level for the 10% set point tests was 12% (corresponding to a chute level of 2320 mm) while the mean chute level for the 90% set point tests was 56% (corresponding to a chute level of 2760 mm). While the chute level set point was closely achieved for the 10% set point tests, it was not achieved for the 90% set point tests. The reason the chute level set point was not achieved for the 90% set point tests was that the cane conveyor was operating at its maximum speed and could not feed sufficient prepared cane into the Donnelly chute to maintain the higher chute level. From this information, it is clear that the rate was higher with the higher set point.

The difference in first mill turbine speed was only 0.2% between the two chute point results, and higher for the 10% chute level tests.

The difference in fibre rate between the two tests was 0.4 t/h, or 0.5%. Taking into account the difference in turbine speed, the difference in fibre rate increases to 0.7%, with the fibre rate being higher for the 90% chute level set point tests. The difference in mean roll lift was 0.4 mm. Given that the delivery nip work opening without lift for the mill was estimated to be 54 mm, the difference in mean roll lift was about 0.7%, reasonably compatible with the fibre rate estimate of change.

The increase in chute level between 12% and 56% is 440 mm and the estimated increase in fibre rate between these two chute levels was 0.7%. Using the conventional chute theory of Murry and Hutchinson (1958) and a typical compression curve for prepared cane, the expected increase in fibre rate is 2.3%. The estimated increase in rate is, then, less than one-third that expected from the conventional theory, providing some justification for the extended model.

Given that the extended chute theory predicts a lower rather than higher rate with higher chute level, the conventional chute theory appears closer to the measured result than the extended theory. It seems, then, that there are considerable energy losses not accounted for in the extended theory. There is, nonetheless, some justification for taking the effect of the falling prepared cane into account.

Discussion of results

Based on experimental evidence, there is some justification for expecting a higher rate from a higher chute level set point. The increase in rate, based on the experimental data, is not large and only about one-third that predicted by conventional theory. For Tarumã’s 78 inch milling train, increasing the chute level set point from 2.3 m to 2.8 m increased the crushing rate by about 0.7%, or about 4 t/h based on a crushing rate of 640 t/h. The effect would most likely have been greater at lower chute levels but still less than conventional theory would predict.

Given the small increase in rate gained by controlling chute level at a high level over a narrow range, it is questionable whether the rate benefit compensates for the increased variability in conveyor speed that is required to maintain the chute level set point and the loss in preparation and extraction that is caused by the variability. The option of having a lower chute level set point and a much wider chute level measurement range, allowing chute level control with smaller changes in speed, deserves further investigation.

Conclusions

Conventional wisdom indicates that high chute level leads to high capacity. That wisdom is based on a model of chute behaviour that ignores the positive benefit of prepared cane falling from the top of the chute to the mat of cane.

An extended model of chute behaviour that takes into account the falling cane predicts that low chute level leads to higher capacity, but that model does not take into account any energy losses in the falling cane. The true effect is expected to lie between the extremes predicted by the two models.

An experiment to measure the effect of chute level found that, at least for the one particular chute, higher capacity with higher chute level was achieved although the effect was only about a third of that predicted by the original model.

Given these results, it is questionable whether the strategy of trying to keep the feed chute full by having fast acting control over a small chute level control range is the best approach. Given the relatively small loss in capacity by operating with a lower chute level, the strategy of operating with a lower chute level, a wider chute level control range and slower acting control system is considered preferable, resulting in more consistent feed to the mill and less risk of the feed chute overflowing.

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EFFET DU NIVEAU DANS LA TRÉMIE SUR LA CAPACITÉ DE L'USINE

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**MOTS CLES: Trémie, Moulin, Capacités,
Niveau, Modèle, Contrôle.**

Résumé

DANS DE NOMBREUSES usines le dispositif d'alimentation du premier moulin fonctionne avec un niveau élevé dans le but de maximiser le tonnage de canne aux moulins. On essaye de contrôler le niveau dans une fourchette serrée, vers le haut de la trémie; cela peut causer des changements rapides du taux d’alimentation des cannes afin de maintenir la consigne d'alimentation. Cet article passe en revue la théorie qui prédit un taux plus élevé de canne aux moulins avec un niveau plus élevé dans la trémie. Il discute aussi la principale faiblesse de cette théorie: elle ne tient pas compte de l'effet bénéfique sur la capacité de la chute des cannes sur la surface supérieure de la canne entrant au moulin. Une extension au modèle est décrite; elle prédit une capacité plus élevée avec un niveau inférieur à la trémie, causée par l'effet de la chute de la canne. Le modèle original et ce modèle élargi semblent être les limites supérieure et inférieure de l'effet réel. L'article présente une expérience qui a mesuré l'effet réel du niveau dans la trémie sur la capacité. On peut conclure que l'augmentation du niveau donne une plus grande capacité, mais l’augmentation est seulement un tiers de celle prédite par la théorie originale. On se demande si une capacité légèrement supérieure est vraiment avantageuse vis-à-vis des coûts causés par un control difficile du niveau vers le haut de la trémie.

EFEITO DO NÍVEL DE CHUTE NA CAPACIDADE DE MOAGEM

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PALAVRAS-CHAVE: Chute, Moenda, Capacidade, Nível, Modelo, Controle.

Resumo

EM MUITAS FÁBRICAS, o chute de alimentação da primeira moenda é operado em nível alto para maximizar o índice de cana pela moenda. Há uma tendência em tentar controlar o nível do chute com uma pequena variação de controle próxima ao topo do chute, o que pode resultar em mudanças rápidas na alimentação de cana para manter o *set point* do chute. Este trabalho revisa a teoria que prevê maior índice de cana com um nível maior do chute e discute o principal ponto fraco dessa teoria, que não considera o efeito benéfico sobre a capacidade da cana em cair do topo do chute ao topo da superfície da esteira. Uma extensão do modelo teórico do chute é descrita, a qual prevê maior capacidade com menor nível do chute, devido ao efeito da queda da cana. Acredita-se que os modelos original e estendido sejam os limites maior e menor em relação ao seu efeito real. Este trabalho relata um experimento que mediu o efeito real do nível do chute sobre a capacidade e descobriu que aumentar o nível do chute não resulta em uma maior capacidade, mas que essa tendência tem apenas um terço da força prevista pela teoria original. O trabalho questiona se os benefícios de uma capacidade um pouco maior compensam os custos de operação com a pequena variação de controle próxima ao topo do chute.