MILL FEEDING: BACK TO BASICS

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Abstract

This paper describes a few of the classic theories on mill feeding and reinforces some of the general principles on this subject. It is evident that a change in mill throughput can be achieved by changing the mill speed or the work opening. The latter is independent of the set opening and can only be changed by altering the feed characteristics. One of these characteristics is the feed opening. For a particular mill configuration there is a feed opening which results in the maximum throughput at the same speed. However, this maximum can be limited due to insufficient roller roughness causing slippage. The feed opening affects mill torque and the forces acting on the mill housing.

Keywords: milling, mill feeding, mill chute opening

Introduction

Mill capacity and/or performance is a combination of throughput and extraction. These are two competing aspects, in the sense that an increase in throughput is usually at the expense of extraction, and *vice versa*. Throughput is determined by mill speed and work opening. Although there is probably an optimum combination which gives the best extraction at the same throughput, it is believed that, in general, mills can benefit from a greater work opening and reduced speed. The main way of changing that work opening is changing the feeding characteristics. This can be the characteristics of the bagasse or the characteristics of the mill itself. In a modern mill with a hydraulically loaded floating top roll, the work opening is virtually independent of the set opening and therefore the settings of the feed and discharge rolls have very little effect on throughput.

There have been extensive studies on the theory of mill feeding. Most of these studies concentrate on two roller mills (Crawford, 1955, 1970; Murry and Holt, 1967; de Boer, 1972) but apply equally to mills with more rolls. The Australians, seen by many as the forerunners in milling, have put these theories into practise with the implementation of pressure feeders and chute flap control. The Brazilian pre-dewatering device is also a typical application of the feeding theory in an effort to improve milling performance, and some of the Brazilian mills are currently rated among the best in the world. This paper looks at some of these old theories to reinforce the general principles of mill feeding that are still true today.

The volumetric theory of mill feeding

Milling is primarily a volumetric process in which a volume of bagasse is compressed between heavy duty rollers with a diameter (*D*) approximate half the roll length (*L*). In a modern mill, the bagasse is presented to these rollers via a diverging bagasse chute (Donnelly chute) with a fixed or variable discharge opening (*H*) and a feed angle (α). At this opening the bagasse has a certain bulk density (*G*). In the axial plane, the opening between the two rolls is minimal and is called the work opening (*W*). The circumferential roll speed (*S*) controls the bagasse throughput (*Q*). A typical two roller mill configuration is shown in Figure 1.

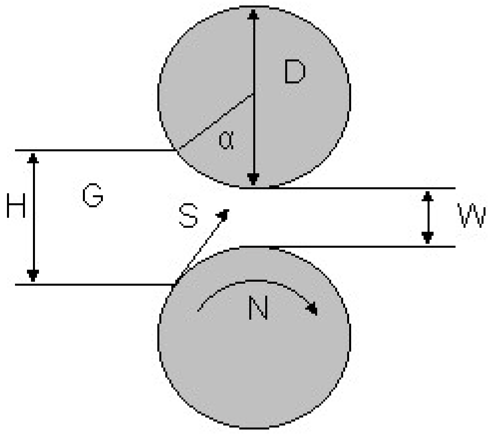

Figure 1. The volumetric feed model.

Fixed top roll

Under ideal conditions with no slip or reabsorption, the bagasse mass (*Q*) entering between the rolls is equal to the bagasse density (*G*) multiplied by the escribed volume at that point. The escribed volume is equal to the product of the roller length (*L*), the feed opening (*H*) and the horizontal component of the velocity (*S*). This horizontal component is equal to the roll speed times the cosine of the feed angle (α). This leads to the following formula for the bagasse throughput:

$$Q = G * L * H * S * \cos \alpha \qquad (1)$$

For a given mill configuration the bulk density of the feed is constant, and depends on the cane properties and how they change through the action of any preceding equipment such as the shredder, any leading mills and feeding devices. The physical size of the feed opening determines the feed volume presented to the mill. This opening can sometimes be altered to accommodate a change in throughput. The angle (α) varies with the feed opening. From the mill geometry it follows that *cos* α is a function of the roll diameter (*D*), the work opening (*W*) and the feed opening (*H*):

$$\cos \alpha = (D + W - H) / D \qquad (2)$$

Substituting equation [2] in equation [1] eliminates the feed angle (α) and results in an expression for the bagasse throughput (*Q*) as a function of its bulk density (*G*), the roller length (*L*), the feed opening (*H*), the roll circumferential velocity (*S*) and the work opening (*W*):

$$Q = G * L * H * S * (D + W - H) / D \qquad (3)$$

Table 1 shows this throughput (*Q*) for various feed openings based on a roll diameter (*D*) of 900 mm, a roll length (*L*) of 2000 mm, a circumferential speed (*S*) of 9 m/min, a bagasse feed density (*G*) of 200 kg/m^3 and a work opening (*W*) of 20 mm. Also shown are the selected work opening (*W*) and some other calculated parameters such as the feed angle (α), the escribed volume at the feed opening (*Eh*), the escribed volume at the work opening (*Ew*), a factor (*K*) and the compaction ratio (*C*). The factor K is equal to the bulk density times the compaction ratio. With a constant work opening (*W*) the escribed volume (*Ew*) at that opening is obviously also constant. The compaction ratio is the same as the ratio of the escribed volumes (*Eh/Ew*) and the ratio of the said factor and the bulk density (*K/G*). It varies over the full range of feed openings.

Table 1. Mill data with fixed work opening.

H mm	α deg	Q t/h	W mm	Eh m^3/min	Ew m^3/min	K kg/m^3	G kg/m^3	C
50	14.8	10.4	20.0	0.87	0.36	483	200	2.42
100	24.3	19.7	20.0	1.64	0.36	911	200	4.56
150	31.2	27.7	20.0	2.31	0.36	1283	200	6.42
200	36.9	34.6	20.0	2.88	0.36	1600	200	8.00
250	41.9	40.2	20.0	3.35	0.36	1861	200	9.31
300	46.5	44.6	20.0	3.72	0.36	2066	200	10.33
350	50.7	47.9	20.0	3.99	0.36	2216	200	11.08
400	54.7	49.9	20.0	4.16	0.36	2311	200	11.56
450	58.5	50.8	20.0	4.23	0.36	2350	200	11.75
500	62.2	50.4	20.0	4.20	0.36	2333	200	11.67
550	65.7	48.8	20.0	4.07	0.36	2261	200	11.31
600	69.2	46.1	20.0	3.84	0.36	2133	200	10.67
650	72.5	42.1	20.0	3.51	0.36	1950	200	9.75
700	75.8	37.0	20.0	3.08	0.36	1711	200	8.56
750	79.1	30.6	20.0	2.55	0.36	1416	200	7.08
460	59.3	50.8	20.0	4.23	0.36	2351	200	11.76

Note: The figures in the bottom row correspond with maximum throughput.

Formula (3) is a quadratic equation in H. The throughput (*Q*), the escribed volume at the feed opening (*Eh*), the factor (*K*) and the ratios (*Eh/Ew*) and (*K/G*) have therefore maximum values at a certain feed opening. This opening can be found by differentiating equation (3) with respect to H and equating the outcome of this differentiation to zero. This results in the following formula for the maximum feed opening (*Hmax*):

$$Hmax = (D + W) / 2 \qquad (4)$$

Combining equation (4) with equations (3) and (2) gives the maximum throughput (*Qmax*) and matching feed angle (*αmax*). Because the work opening is usually small in comparison with the roll diameter, the feed opening and feed angle that give the maximum throughput are approximately equal to half the roll diameter and 60° respectively. The different parameters related to the maximum are given in the last row of Table 1.

Floating top roll

For a hydraulically loaded floating top roll the work opening (*W*) is not fixed but is a function of the throughput. This function is rather complicated but can be simplified by the assumption that the throughput is equal to a factor (*K*) times the escribed volume at the work opening. This escribed volume is equal to the product of the roller length (*L*), the work opening (*W*) and the roll circumferential velocity (*S*):

$$Q = K * L * W * S \qquad (5)$$

This assumption implies a constant juice extraction independent of the throughput. This is not entirely correct, although the error is small and does not detract from the general principle.

Combining equation (5) with equation (3) while eliminating the work opening leads to the following expression for the throughput (*Q*) as a function of the factor (*K*), the roll length (*L*), the roll velocity (*S*), the roll diameter (*D*), the feed opening (*H*) and the bagasse density (*G*):

$$Q = K * L * S * D * (H / D - (H / D)^2) / (K / G - H / D) \qquad (6)$$

Table 2 shows, for the same feed openings, the identical parameters as listed in Table 1, i.e. the throughput (*Q*), the feed angle (α), the work opening (*W*), the escribed volumes at the feed opening (*Eh*) and the work opening (*Ew*), the factor (*K*), the bulk density (*G*) and the compaction ratio (*C*). The values are again based on a roll diameter (*D*) of 900 mm, a roll length (*L*) of 2000 mm, a circumferential speed (*S*) of 9 m/min and a bagasse feed density (*G*) of 200 kg/m^3. In addition, they are based on a factor (*K*) of 1600 kg/m^3 instead of on the work opening, which is no longer an independent variable. At a fixed work opening, the compaction ratio changes with a change in feed opening. With a variable work opening, the compaction ratio is approximately constant.

Table 2. Mill data with variable work opening.

H mm	α deg	Q t/h	W mm	Eh m^3/min	Ew m^3/min	K kg/m^3	G Kg/m^3	C
50	18.0	10.3	5.9	0.86	0.11	1600	200	8.00
100	25.7	19.5	11.3	1.62	0.20	1600	200	8.00
150	31.7	27.6	16.0	2.30	0.29	1600	200	8.00
200	36.9	34.6	20.0	2.88	0.36	1600	200	8.00
250	41.6	40.4	23.4	3.37	0.42	1600	200	8.00
300	45.9	45.1	26.1	3.76	0.47	1600	200	8.00
350	50.0	48.6	28.1	4.05	0.51	1600	200	8.00
400	54.0	50.8	29.4	4.24	0.53	1600	200	8.00
450	57.8	51.8	30.0	4.32	0.54	1600	200	8.00
500	61.5	51.6	29.9	4.30	0.54	1600	200	8.00
550	65.1	50.0	29.0	4.17	0.52	1600	200	8.00
600	68.7	47.1	27.3	3.93	0.49	1600	200	8.00
650	72.2	42.9	24.8	3.57	0.45	1600	200	8.00
700	75.8	37.2	21.5	3.10	0.39	1600	200	8.00
750	79.3	30.1	17.4	2.51	0.31	1600	200	8.00
465	58.9	51.9	30.0	4.32	0.54	1600	200	8.00

Note: The figures in the bottom row correspond with maximum throughput.

Under these conditions the throughput (*Q*), the work opening (*W*) and the escribed volume at the feed opening (*Eh*) are at a maximum at a specific value of the feed opening. With a constant factor K, the only dependent variable on the right hand side of equation [6] is again the feed opening and this maximum can again be found by equating to zero the first derivative with respect to H.

This feed opening (*Hmax*) is a function of the roll diameter (*D*) and the ratio of a factor (*K*) and the bulk density of the feed (*G*):

$$Hmax = D * K / G * (1 - (1 - G / K)^{0.5}) \qquad (7)$$

Combining equation (7) with equations (6), (5) and (2) gives the maximum throughput (*Qmax*) and corresponding work opening (*Wmax*) and feed angle (αmax). Parameters related to the maximum are given in the last row of Table 2. It is interesting to note that the ratio of the maximum feed opening and the roll diameter (*Hmax/D*) is in fact only a function of the compaction ratio (*C*).

Throughput
Figure 2 displays the throughput as a function of the feed opening. The blue line shows that function for a fixed work opening of 20 mm (Table 1, column 3). The red line shows the same function for a floating top roll with a variable work opening dependent on the feed opening (Table 2, column 3). With a floating top roll the maximum throughput (*Qmax*) is 51.90 t/h at a feed opening (*Hmax*) of 465 mm and a work opening (*Wmax*) of 30 mm. Because the fixed work opening (*W*) of 20 mm is lower than the maximum work opening with a floating top roll, the maximum throughput (*Qmax*) is lower at 50.78 t/h at a feed opening (*Hmax*) of 460 mm. For a fixed work opening larger than 30 mm, both the maximum throughput and the corresponding feed opening will be greater than those for a variable work opening. However, this increase in the maximum throughput is accompanied by a reduction in the compaction ratio.

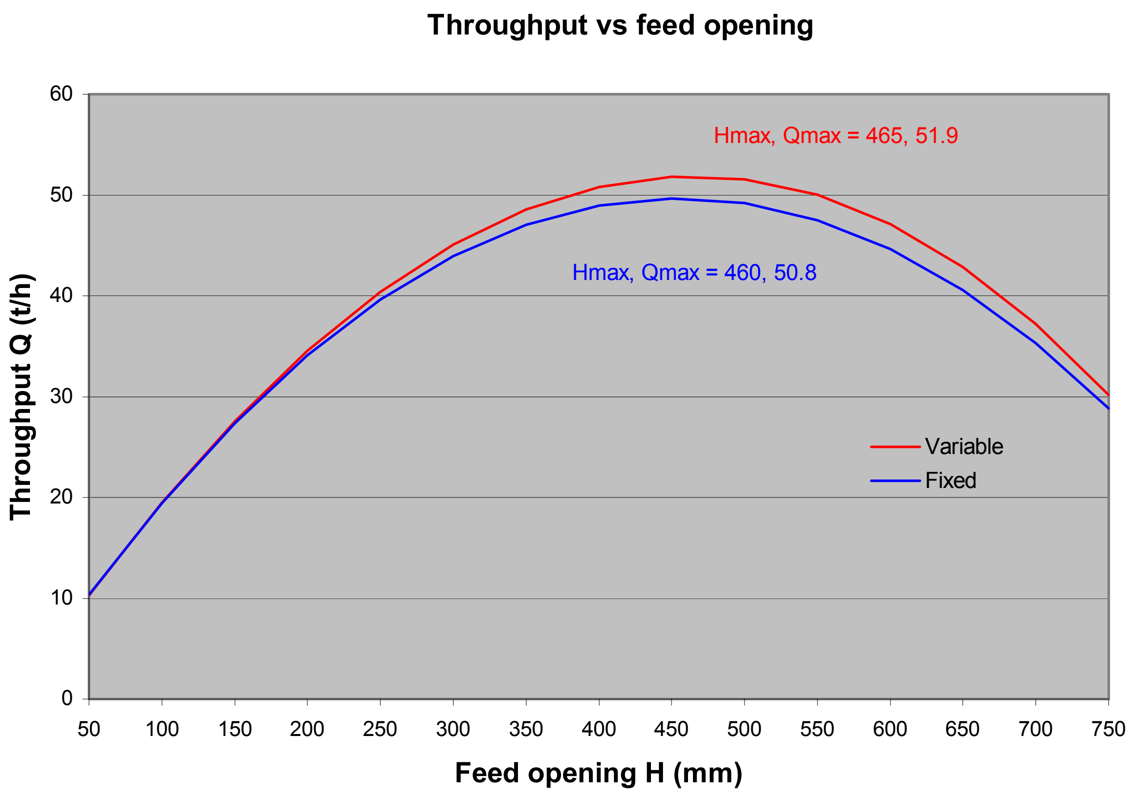

Figure 2. Throughput as a function of the feed opening.

The volumetric theory of mill feeding can also be approached with the focus on fibre throughput (*Qf*) and the fibre fills (fibre fill = tons fibre divided by the escribed volume) of the feed (*Ih*) and work opening (*Iw*). This approach, which leads to the same results, is very much a repeat of the above and is only briefly given in the Appendix. The compaction ratio (*C*) is equal to the ratio of the escribed volumes (*Eh/Ew*), the ratio of the fibre fills (*Iw/Ih*) and the ratio of the factor K and the bulk density (*K/G*).

The dynamics of mill feeding

The dynamics of mill feeding form an integral part of a feeding theory and are of fundamental importance. Some efforts have been made to describe these dynamics. This is, however, substantially more difficult than a volumetric description and successes have been few. The main focus of mill feed dynamics is on the effect of the feed opening on mill load and torque and on the friction between the bagasse and the mill roll surfaces.

Friction and feed opening

Adequate friction between the bagasse and the roll surface is critical to mill feeding. A smooth roll with a low friction coefficient can limit the maximum feed opening. The forces acting on the bagasse by the roll are identical in magnitude but opposite in direction to the forces exerted by the roll on the bagasse. Figure 3 shows these forces at the feed opening.

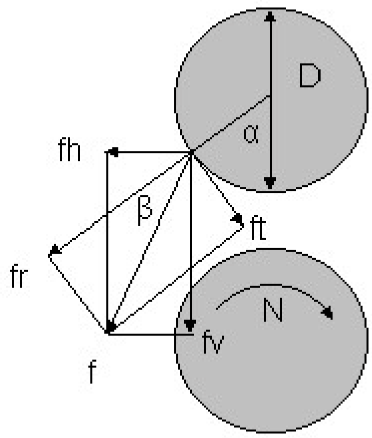

Figure 3. The friction feed model.

The maximum tangential force (*ft*) is equal to a friction coefficient (μ) multiplied by the radial force (*fr*):

$$ft = \mu * fr \qquad (8)$$

This friction coefficient (μ) can be expressed as a function of the angle ($\exists$), which is usually referred to as the angle of friction:

$$\mu = tan\ \exists \qquad (9)$$

The resultant horizontal force (*fh*) is equal to the algebraic sum of the horizontal components of the radial (*fr*) and tangential forces (*ft*):

$$fh = fr * sin\ \tilde{\alpha} ft * cos\ \alpha \qquad (10)$$

In order to maintain a positive feed into the mill without the aid of an external feeding device, this horizontal component (*fh*) must be smaller than zero. With the help of equations (8), (9) and (10) it can be shown that in order to achieve this the friction angle ($\exists$) must be greater than the feed angle (α). If the friction angle is smaller the maximum feed angle decreases accordingly.

Mill load and torque

The forces acting on the mill roll surface due to the pressure (*P*) in the bagasse are a radial force (*Fr*) and a tangential force (*Ft*) (Figure 4). The latter follows from the product of pressure and a friction coefficient (μ). These forces can be found by integration over the roll area (*D, L*) on which the pressure is acting. However solving the integrals has so far been unsuccessful due to a lack of knowledge about the pressure and the friction coefficient as a function of the angle (*2*).

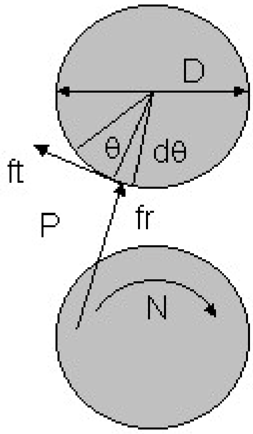

Figure 4. Diagram of roll forces.

The radial force exerted by the bagasse on the mill roll:

$$Fr = D * L / 2 * \mu P \, d2 \qquad (11)$$

The tangential force acting by the bagasse on the mill roll:

$$Ft = D * L / 2 * \mu \, \mu * P \, d2 \qquad (12)$$

The resultant vertical force (mill load) due to the radial and tangential forces:

$$Fv = D * L / 2 * \mu \, (P * cos \; 2 + \mu * P * sin \; 2) \, d2 \qquad (13)$$

The resultant horizontal force due to the radial and tangential forces:

$$Fh = D * L / 2 * \mu \, (P * sin \; \tilde{2} \; \mu * P * cos \; 2) \, d2 \qquad (14)$$

In the case of a hydraulically loaded floating top roll, the net resultant vertical force (*Fv*) is equal to the hydraulic force (load). The torque is half the diameter (*D*) multiplied by tangential force (*Ft*). This torque is the same for both rolls and the total torque (*Tt*) as seen by the mill drive is therefore twice as high:

$$Tt = D^2 * L / 2 * \mu \;\; \mu * P \, d2 \qquad (15)$$

Changing the feed opening while operating with a fixed top roll alters the compaction ratio (*C*), with a maximum at a specific work opening (see Table 1). It seems logical that the pressure is a function of the compaction ratio and displays a maximum at the same feed opening. In addition, a change in feed opening alters the area of the roll on which the pressure acts.

With no restriction in the opposing vertical roll force (roll load) it can indeed be expected that these combined effects result in an increase in mill torque with an increase in feed opening up to the point where the compaction ratio is at a maximum. This will be accompanied by an increase in the vertical and horizontal reaction forces.

With a floating top roll the compaction ratio (*C*) is independent of the feed opening (see Table 2). Any change in torque as a result of an alteration in the feed opening is therefore mainly due to a change in the area on which the pressure acts. However the resultant vertical force must be equal to the hydraulic force which is almost constant. To comply with this requirement the pressure must find a new equilibrium to compensate for any change in active area. Because of these two opposite effects one would expect very little change in torque, if any. In practise however, it is found that mill torque increases with an increase in feed opening for which there may be various reasons. A discussion of these reasons is beyond the scope of this paper.

Discussion

The above theories are based on a number of assumptions which are normally not true in practise. For example they assume that there is no slip and reabsorption, that the chute is placed symmetrically in relation to the rolls, and that bagasse behaves as a homogeneous material. Milling is not an exact science and it is an illusion to believe that any milling theory can provide the solutions to all problems. They can, however, improve general understanding and provide common guidelines. The calculations carried out in this paper should be seen in this light and are given mainly for illustration purposes. It is not possible to calculate the optimal feed opening (if such a thing were to exist). However, the classic theories on mill feeding discussed here have made significant contributions to the improvement of the milling process, and engineers should take cognisance of these theories.

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APPENDIX

The throughput in tons fibre (Qf) can be expressed as a function of the fibre fill at the feed opening (Ih), the roll length (L), the feed opening (H), the circumferential speed (S) and the cosine of feed angle (α):

$$Qf = Ih * L * H * S * \cos\alpha \qquad (1)$$

Mill geometry results in a equation for *cos α* as a function of the roll diameter (*D*), the work opening (*W*) and the feed opening (*H*) as follows:

$$\cos\alpha = (D + W - H) / D \qquad (2)$$

Substitution of the right hand side of this equation in formula [1] eliminates the feed angle (α) from the expression for the throughput in tons fibre:

$$Qf = Ih * L * H * S * (D + W - H) / D \qquad (3)$$

The throughput in tons fibre is a quadratic function in H and has a discreet maximum at a specific feed opening (Hmax) which for a fixed work opening can be found from the first derivative with respect to H:

$$Hmax = (D + W) / 2 \qquad (4)$$

The tons fibre can also be expressed as a function of fibre fill at the work opening (Cw) multiplied by the escribed volume at that opening:

$$Qf = Iw * L * W * S \qquad (5)$$

Equations (3) and (5) can be combined while eliminating the work opening:

$$Qf = Iw * L * S * D * (H / D - (H / D)^2] / (Iw / Ih - H / D) \qquad (6)$$

When assuming a constant fibre fill (Cw) independent of the fibre throughput, the maximum throughput can again be found from the first derivative with respect to H:

$$Hmax = D * Iw / Ih * (1 - (1 - Ih / Iw)^{0.5}) \qquad (7)$$

The ratio of the fibre fills (Iw/Ih) is equal to the compaction ratio (C).