AGGLOMERATION DRUM SELECTION AND DESIGN PROCESS

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1. Abstract

A model has been developed by for drum agglomeration; which allows selection of geometry and power input. Specific aspects considered are:

- Calculation of total static and operating volumes
- Solids residence time based on operating volume
- Selection of the aspect ratio
- Selection of different operating fill to suit the feed opening
- Selection of proportion of critical speed
- Calculation of shell and motor power requirements.

The model uses solids total residence time to calculate the required operating volume. The burden density is calculated from the solids bulk density and the fluid density. Power is calculated using the Liddell and Moys correlations for burden position and shape, and the operating drum speed. A further power allowance is made to allow for accretion drop off during drum rotation.

Results from the model (especially power) have been verified from industrial installations of significant size. Predicted and observed power draws are within 5% when burden slip and bypassing is not significant. When these are significant (at higher fill percentages >15%) the actual power draw will be less than the model prediction.
2. Introduction

The design and selection of drum agglomerators is an inexact science at best with little published data on selection criteria or calculation procedure. To date, most agglomerators have been selected on simple criteria, such as global solids residence time rather than more rigorous criteria such as “degree of agglomeration”. Some models have been attempted by research organisations to consider the degree of agglomeration question but they have not been released into the public domain. Significant work has been done on kilns and dryers. However these generally operate at much lower fractions of critical speed than agglomerators and have discharge weirs that are not used in agglomeration. As a result the models generated for kilns are not generally applicable to agglomerators.

A similar situation exists for grinding mills. These operate at high proportions of critical speed with very high levels of burden loading. This is further complicated by the inclusion of grinding media and the interaction between this and the out-flow system (over-flow or grate discharge).

The current typical drum agglomerator size selection, process considers the physical selection of the agglomerator geometry and drive power. It is based on testwork results that define the residence time required to provide the required degree of agglomeration. The degree of agglomeration is a combination of size aggregation and work hardening of the aggregates. Agglomeration of fine materials has been shown by [Mishra et al] to occur within two revolutions of the drum, when the agglomerating fluid is added at the toe of the cascading burden. After this period the size distribution fluctuates in a small band showing continued agglomeration and a balance of agglomerate breakages. The time (or number of revolutions) required to work harden the agglomerates is the ‘real’ determinant of the required residence time. This is in turn quantified by physical strength tests such as: drop shatter, squeeze and crack or deformation under an applied load without cracking.

Other work has been done by the Tata Institute in India, on pelletising of iron ore fines up to 10 mm diameter [Kapur and Runkan]. They have developed a number of particle population dynamic models and growth kinetics. The results are consistent in that most particles above 1.0 mm act as seeds and that all growth is completed (and all fines agglomerated) within one minute. In fact their work suggests that most (over 95%) of the agglomeration is completed in the first 0.5 minutes with a minimum agglomerate diameter of 2.0 mm.

The largest effective control parameter on agglomerate size distribution is the total moisture [Kapur and Runkana].

In most cases the residence time will be determined from results from either batch testing or continuous pilot (or bench) testing. In both cases it is assumed that the solids residence time is the important parameter. This is obtainable directly from the batch test or by back calculation from this model for a continuous test. In either case the continuous flow agglomerator needs to be selected to achieve the necessary solids residence time and degree of agglomeration,

The present model is set out in a number of sections that each calculates some aspect of the agglomeration activity. These sub-models are discussed in detail in the following sections. A validation check has also been made on the overall model result to check the calculated power against field results.
3. Residence Times

3.1 Machine Solids Residence Time

The solids residence time model is used to calculate the overall agglomerator parameters. In reality there will be a residence time distribution function for all solids of varying size and mobility. This distribution function is very close to plug flow, even for long units such as rotary kilns [Ang et al, Abouzeid et al and Sai et al]. The approach adopted in this work is a simple plug flow model assuming total radial mixing and no axial dispersion. At present there is no further information included on a potential residence time distribution of the solids. The plug flow assumption is probably highly valid considering the results of the RTD work of the referred authors. Further refinement of this aspect awaits more fundamental work to be published.

The assumption is that the residence time of the solids is based on coarse material occupying a volume set by the dry uncompacted bulk density of the solids. This needs to be differentiated from the total bulk density, which includes the agglomeration solution. Values of fraction of solids in the agglomerate will vary from the minimum body-centered-cubic mono sphere of 0.52 (=π/6) to as high as 0.85 for a wide range of particle size. If instead the solids volume fraction is known the dry bulk density can be calculated from

$$\rho_b = \varepsilon_p \rho_p$$

The volume occupied by the solids is set by the diameter of the agglomerator and the operating angle, rotational speed and throughput. It is not sensitive to flow restrictions such as ring dams or baffles [Sai et al]. All of these parameters interact to generate the machine determined operating residence time. At very low feed rate the agglomerator solids volume will approach zero if the unit is not fitted with a discharge ring.

The volumetric flow rate of the solids, and the agglomerator operating solids volume (hold up) provide the solids average residence time.

3.2 Residence Time Calculation

Various relationships have been identified for the residence time, as a function of the operating angle and other operating variables. The simplest is the consideration of the "single particle" trajectory as a function of θ, L, D, N [Perry 1]. This simple relationship for residence time is:

$$\phi = 0.19L/(NDS)$$

An alternate model [Perry 3] that attempts to account for some wall slip, takes the form:

$$\phi = 0.23L/(N^{0.6}DS)$$

This calculation is the pathway length and operating trajectory of a single particle lifted with the rotation friction of the drum and then rolling to a lower level under gravity through a number of cycles.

A more rigorous approach is to take the actual burden shape into account where the particle is assumed to be lifted with the drum rotation and then to roll down the cascading face of the angle of repose in the drum burden. Early models for kilns and dryers took into account the static angle of repose rather than the dynamic angle of repose. For operating speeds at low percentage of critical the error introduced by these models is low. However for higher operating speeds this error can be significant as discussed in a later section. When such models are utilised the general form (in foot units) is [McClellan and Van Zyl]:

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---
\[ \phi = 1.77(AL)^{0.5}/(NDS) \]

For use with metric measurements and dynamic operation A should be replaced with \( \alpha \) (radians):

\[ \phi = (0.3048)^{0.5} \times 1.77(\alpha L)^{0.5}/(NDS) \]

\[ \phi = 0.977(\alpha L)^{0.5}/(NDS) \]

A comparison of the three models is provided in Figures 3-1 and 3-2. This shows the effect of the alternate path geometry assumption on the calculation of the residence times.

![Residence Time Models](image)

**Figure 3-1 Alternate Residence Time Calculations with Drum Slope.**
In both cases the simple single particle trajectory model under-estimates the residence time. This is around 70% for all operating speeds. The modified single particle trajectory model over-estimates the residence time calculated by the burden shape model by 5% to 12% between 30% and 60% of critical speed. There is not a great difference between the two models. The alternate single particle trajectory model is slightly easier to use as it does not require the addition of the information on the dynamic angle of repose.

The dynamic angle of repose ($\alpha$) is often modified from the material angle of repose ($\alpha_m$) to take account of the operating situation. The ‘real’ burden angle to the horizontal is a combination of the drum operating angle and the burden dynamic repose angle. This is discussed in detail in a later section.

An assumption inherent in this analysis is that the agglomerating fluid fills some of the voids in the solids burden as part of the agglomerate volume. This serves to increase the agglomerate (particle) bulk density above the dry bulk density. The estimate of the agglomerate particle density needs to be conducted on tested samples to determine the degree of compaction and consolidation necessary to achieve the required characteristics. However the overall total dry bulk density will not be all that different from that determined from the uncompacted bulk density from standard testing procedures. This is because, although the individual agglomerate particle density may be quite high, the agglomerate packing factor is low giving an overall minimal change in total dry bulk density from the ‘normal’ value.

Some support for this approach is provided by Latham et al who have provided some guidance on the estimate of maximum and minimum packing of particles. For a typical crushed ore size distribution with a Rosin-Rammler slope of 0.77, the packing reaches its maximum at 0.85 (voidage = 0.15). Similarly for the agglomerate population size, which typically has a Rosin-Rammler slope of 2.0 to 3.0 and a Power’s roundness of 0.7; the packing is significantly lower at 0.72 (voidage = 0.28). These values give overall packing of 0.61. For a particle density of 2.7 the resultant bulk density is 1.65; not all that different from the usual uncompacted bulk density measurements seen in many heap leach operations.

**Figure 3-2 Alternate Residence Time Calculations with Drum Speed.**
For moisture contents above about 15% (i.e., for high clay content materials) significantly lower dry bulk densities are seen as a direct result of the volume occupied by the extra moisture. For the most difficult ores, the uncompressed dry bulk density can be as low as 1.40 when moisture contents of +20% are evident.

In all models, the residence time is set by the agglomeration drum geometry and mechanical operating conditions. In other words, the residence time is independent of the feed rate. The assumption made is that the burden shape (and volume) does not affect the agglomeration. This is the case up to about 15% to 20% of fill. It is not valid at higher values, as short-circuiting can occur over the top of the burden [Perry 3]. The fill proportion is discussed in the section on validation. It would appear that there is considerable loss of performance above about 15% fill.

The implication is that once the operating parameters are fixed, the proportion of the drum fill is set only by the feed rate. For a low feed rate the operating fill will be low and for a higher feed rate the operating fill will increase to achieve the same residence time. This is confirmed by the work of [Sai et al, Abouzieid et al and Ang et al]. They all demonstrated that this mechanism occurs even with exit dams on the rotating shell. Thus it is possible to generally load the agglomerator up to a limit set by the quality of the product; without significantly decreasing the residence time.

[Ang et al] also showed that the agglomerate particle size did not have any material effect on the residence time and that larger and smaller particles of different densities have similar residence times. Again, this is important for agglomeration as it implies that there will be little difference in agglomerate quality (due only to residence time issues) between larger and smaller sizes.

It is also important in consideration of the agglomerate product size distribution. With little or no difference in residence time with particle size there is no sizing effect in a drum agglomerator that might retain the smaller sizes for further growth. To generate fewer, but larger, agglomerates will need either longer residence time or a recycle of the small agglomerates, as is done for iron ore and fertilizer agglomeration [Abouzieid et al].

### 3.3 Residence Time Distribution

The residence time of the particles and agglomerates in the drum will have a distribution (RTD) dependent on their history within the drum. A number of workers have investigated the RTD for kilns and driers. These tend to have very high L/D ratios and would show a magnified effect of any deviations from plug flow. The RTD studies of [Sai et al] and [Ang et al] confirm that the deviation from plug flow is very small. The axial dispersion rate is four orders of magnitude less than the transport rate. The D/UL (Brodenstein Number Br) is approximately $5 \times 10^{-4}$ [Sai et al]. This is $< 0.01$, the limit usually used to characterise little deviation from plug flow [Levenspiel]. Other work [Abouzieid et al] showed more axial mixing (dispersion) with Brodenstein numbers of the order of 0.02. In this work the variance of the normalised residence time was between $1 \times 10^{-2}$ to $2 \times 10^{-2}$, indicating that there is still little deviation from plug flow.

The degree of deviation from plug flow decreases with those parameters that affect the residence time – operating angle and rotation speed. With lower residence times there is less deviation from plug flow. For agglomerators this would seem to indicate that there is likely to be very little deviation from the plug flow assumption with the relatively short residence times used (1 to 3 minutes). Residence times for the referenced works are:

- Abouzieid – 90 s to 180 s
- Sai et al - 100 to 300 minutes
- Ang et al - 35 to 70 minutes
The operating speed of agglomerators tends to be a much higher percentage of critical than kilns and driers. This increase in internal agitation will produce a greater influence of eddy diffusion on Br. However little data has been published to allow this effect to be evaluated. The results from the references cited show a range of Brodenstein numbers:

- Abouzeid – 28% Nc -> Br = 0.025
- Sai et al - 1.8% Nc -> Br = 0.0003904
- Ang et al – 2.7% Nc -> Br = 0.00046

These are shown in Figure 3-3.

The higher the percent of critical speed the higher the Brodenstein number and the greater is the axial dispersion. However the effect of the axial dispersion is still small in relation to the overall residence time and can be generally discounted for engineering purposes.

Figure 3-3 Effect of Operating Speed on Broednstein Number (Axial Dispersion)
4. Aspect Ratios

4.1 Drum Aspect Ratio

The aspect ratio of the drum (L/D) is generally kept in the region of 2:1 to 5:1 [Perry 2]. However longer or shorter units have been installed depending on the availability of vendor standard equipment to meet the required design criteria.

Normal ranges are between 1.5:1 to 5:1 with a preponderance around 3:1. Some operational experience tends to a 4:1 ratio for agglomerates formed with pozzuolana [Pyper and Pangbourne, McClellan and Van Zyl] and shorter (with larger diameter) when relying on physical agglomerate quality from capillary coherence [Bernard]. Larger diameter units have higher rates of consolidation (work hardening) than smaller diameter units. However the degree of overall consolidation is also still directly related to the residence time. In other words, for more consolidated agglomerates a larger diameter and shorter unit is preferable.

One of the drivers of shorter agglomerators is the diameter of the feed opening as discussed later. With higher percent fill operations the spillage from the feed opening can be the constraint on the feed rate. In all cases for agglomerators it is assumed that the discharge end is open and does not have a circular dam as is common for kilns and driers.

For the L/D parameter there are no set values. The actual geometry is at the control of the design engineer.

4.2 Load Aspect Ratio

The aspect ratio of the load can change with the operating parameters selected for the unit. For a given drum geometry and mechanical conditions there will be a ‘carrying capacity’ that these determine [Sai et al]. This capacity is the feed rate at which the burden in the drum assumes a nearly flat profile. This is illustrated by Figure 4-1 which shows conditions of feed at, above and below the carrying capacity.
Figure 4-1 Drum Carrying Capacity Profiles with varying Feed Rates.  
(After Sai et al)

These profiles are for a kiln with a discharge weir(s). They are not directly applicable to the open ended agglomerator but are a good illustration of the effect of feed rate. For feed rates below the carrying capacity, the bed profile tends to a flatter slope; while for higher feed rates the slope from feed to discharge increases. As the feed rate increases further, the overall slope of the burden surface increases to provide the necessary potential to move the large tonnages to the discharge end.

This increasing burden slope will increase the operating fill proportion (particularly at the feed end). The physical size of the feed dam will set the maximum operating burden level and hence the maximum throughput of a given drum geometry.

The data from Abouzeid indicates that there is little change in the burden profile for the low aspect ratio drum that he used. His 3:1 drum is far closer to agglomeration practice than those of Sai et al (40:1) and Ang et al (35:1). Under these conditions it is likely that the drum burden will be influenced mostly by the operating angle and assume a surface profile that is nearly the same along its length.

4.3 Feed Opening

The feed opening, by necessity, is circular and needs to be such that bridging and blockage are minimised. It also needs to be smaller than the burden operating level at the feed end of the unit, to minimise spillage from here. As a result, the calculations of the agglomerator operating volume (and feed end surcharge height) need to be part of the overall selection of the feed diameter.

The sizes of feed opening requirements for most agglomerators will tend to limit the operating volume that can be utilised quite significantly. A feed opening of 1.0 m diameter (for the feed chute and fluid addition points) will limit the maximum fill proportion to that shown in Table 4-1.
Table 4-1: Max Percent Fill for Drum Diameters with a 1.0 m Diameter Feed Chute and 0.15 m Spillage Clearance above the Feed End Burden Depth.

<table>
<thead>
<tr>
<th>Dia: m</th>
<th>1.5</th>
<th>1.75</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill: %</td>
<td>2.9</td>
<td>7.5</td>
<td>11.8</td>
<td>18.5</td>
<td>23.2</td>
</tr>
</tbody>
</table>

When considering the restrictions in the minimum feed opening alone, it is evident that the operating fill is unlikely to be greater than 20% of the total volume. It is also clear that the larger drum diameters are less prone to feed end spillage as there will be greater clearance between the top of the burden and the feed opening. This is another factor in selection of shorter and ‘fatter’ drums.
5. Burden Density

The burden density is calculated from the combination of the solids dry bulk density and the fluid density filling some of the voids in the burden. When the particle content, particle density and solution density are known, with the moisture content of the agglomerated material the burden overall density can be calculated from:

\[ \rho_{\text{burden}} = \varepsilon_p \rho_p (1 + w) \]

where \( \varepsilon_p \) = fraction of volume filled by the solids, and \( w \) is the percent w/w of moisture.

When the dry bulk density and the moisture level are known the burden density is:

\[ \rho_{\text{burden}} = \rho_b (1 + w) \]

As discussed previously the overall dry bulk density is reasonably independent of the agglomerate ‘particle’ density. This is not strictly true. However the change in overall dry bulk density with agglomeration is not great, and the approach can be used as a first approximation until specific material testing has been done.

One other aspect of the bulk density determination is related to materials that have a high moisture retention characteristic. As discussed earlier the agglomerate voidage is likely to be 0.15. Of this voidage approximately 0.03 will be occluded air voids. If the moisture retention is greater than the residual fractional volume then the agglomerate ‘particle’ density will be less than that calculated using the 0.15 voidage and the moisture retention. For these materials the agglomerate density needs to be calculated using the actual moisture retention levels and the occluded air voids. The overall bulk density can then be estimated using the *agglomerate* packing density of about 0.72.

The burden density will be higher than the dry bulk density due to inclusion of the fluid within the solids voids. It is a somewhat conservative estimate (for power calculations) as it assumes no reduction in burden density due to the action of the drum rotation. This is appropriate for the low percentage of critical speed at which agglomerators operate. The action of the burden mass is one of tumbling rather than cascading and little change in burden density is observed until cascading is evident [Liddell and Moys].
6. Outflow Heights

6.1 Circular End Discharge Calculation

The discharge of an agglomerator can be compared to the discharge of a fluid through a circular segment overflow weir. The estimated depth of the discharge is the minimum height required for passage of that equivalent volume of liquid. Consideration of this flow aspect will set a limit of the minimum height that the burden will occupy at the discharge. The burden will however still average the depth required to provide the residence time set by the drum geometry and speed.

The height of the flow over a circular discharge weir has been an issue for calculation for a number of years. It is common in many gravity flow situations but has not been addressed by standard texts on hydraulics. Analytical analysis of the problem shows that there is a resultant integral that is not amenable to resolution other than by numerical methods. A numerical solution to the integral has been obtained and a simplification for engineering use determined [Miller and Newton].

The numerical solution involved use of Simpson’s rule with trapezoidal end correction in 100 discrete steps. The resultant values were modelled with a power law relationship to relate the volume flow to the weir diameter and the depth at the weir invert. The resultant expression is

\[ Q = C_d \cdot D^a \cdot H^c \]

Appropriate values of \(a\), \(b\) and \(c\) agree with the numerical integration solutions with errors of less than 1.6% for \(H < D/3\) (=29% fill). (\(D\) and \(H\) in mm).

This allows the direct calculation of any one of the three parameters without requiring an iterative procedure. The value of the discharge coefficient \(C_d\) is generally the same as for a sharp edged weir. The circular discharge correlations developed by Wemco for their heavy medium baths, [M.C. International] were analysed and the discharge coefficient found to be 0.63. This slightly higher than ‘normal’ value is reasonable with a slightly curved shape to the discharge. A \(C_d\) of 0.61 is recommended.

A comparison of the height calculated from the weir formula and the burden depth to satisfy the residence time criteria shows that for all residence times, the volumetric discharge depth << average operating depth. This can be observed in practice, near the drum discharge where the material sloughs off the burden as the available head exceeds the coherent adhesion within the burden. In general the maximum angle of the burden at the discharge end will be the dynamic angle of repose applied tangentially to the cascading burden. This geometry indicates that the influence of the discharge on the operating fill is limited in extent to not much more than one or two equivalent revolutions.

6.2 Single Particle Trajectory Calculation

The single particle trajectory calculation gives the relationship between the various geometry and mechanical parameters (Diameter, Speed, Angle and Length). By considering the length of the drum and the residence time as a means of calculating the discharge velocity by:

\[ v_d = \frac{L}{\phi} \]

Using the relationships for \(\phi\) and critical speed the equation reduces to:

\[ v_d = 42.3f(D)^{0.55}S \]

As expected the average longitudinal velocity is dependant only on the drum diameter, fraction of critical speed and the slope. The discharge area is:
\[ \frac{Q}{v_d} = \frac{T}{(42.3 \rho_b \cdot f \cdot D^{0.55} \cdot S)} \]

From this area the Segment angle is calculated from:

\[ \text{Segment Area} = R^2(\theta - \sin \theta)/2 \]

This in turn is used to calculate the segment height and other parameters of the burden segment. The geometry of the segment is illustrated in Figure 9.1.
7. Burden Position

The burden shape is modelled by the circular segment that corresponds to the outflow solids operating height. Liddell and Moys confirm this, as one of the most appropriate methods of determining ‘mill’ power. In essence the agglomerator is a medium sized, low density, low speed ‘dry’ autogenous mill with high throughput rates and a dynamic solid rather than slurry burden. The size of the segment is set by the agglomerator geometry and operating parameters (shell diameter, speed and slope) and the solids feed rate and bulk density (exit segment height). The only other parameter required for the calculation of the burden power draw is the angular position of the burden.

Liddell and Moys have provided a relationship between the dynamic angle of repose of the burden with drum rotational critical speed, as illustrated in Figure 7-1. This allows the calculation of the angular offset of the burden, which is used in the power calculation.

- **Figure 7-1 Burden Dynamic Angle of Repose (Liddell and Moys)**

![Figure 7-1 Burden Dynamic Angle of Repose (Liddell and Moys)](image)

The data from mill studies do not extend to the lower fractions of critical speed that are characteristic of agglomerators. The reality is that the minimum burden position is the static angle of repose of the agglomerates (not the feed material). For well rounded agglomerates of moderate size distribution (and low to moderate ‘stickiness’) the static angle of repose is likely to be in the region of 34 degrees (similar to bauxite [Robinson]).

By limiting the minimum operating angle to this value, a revised correlation that passes through the static angle of repose at low fractions of critical speed provides a modified version of the correlation. Similarly at the upper end of the critical speed range the burden dynamic angle approaches infinity – i.e. the load is centrifuging. A new correlation has been developed that is an inverse power relationship between dynamic angle of repose and critical speed with asymptotes at the static angle of repose and 100% critical speed, as shown in Figure 7-2.
The burden position correlation is computed from:

$$\alpha = 34 + 7.41/(1/f-1)^{0.447}$$

In the range of critical speeds used by agglomerators (0.2 to 0.5), the operating dynamic angle of repose varies from the static angle of repose by +2.0° to +8.0°. The range is relatively limited and has only a small effect on the power consumption and other parameters.

The actual burden angle ($\alpha'$) is a combination of the drum operating angle ($\beta$) and the dynamic angle of repose ($\alpha$). The compound angle is the ‘true’ angle of the burden to the horizontal and should be used in the power and residence time calculations.

Considering the geometry of the system the following expression for the real burden angle can be obtained by analysis:

$$\tan^2 \alpha' = \tan^2 \alpha + \tan^2 \beta$$

For typical values of angles: 39 degrees for the dynamic angle of repose and 7 degrees for the drum, the resultant total angle is still only 39.3 degrees. Although included in the calculation it is not particularly significant even up to drum inclination angles of twelve degrees.
8. Speed Calculations

8.1 Critical Speed

The critical speed \( N_c \) is set only by the internal shell diameter. Ranges for operating speed are set by the dynamic burden action that is required. Since agglomeration rather than particle breakage are the required actions, the operating speed tends to be much less than for mills. Mills operate in the range of 70% to 75% of critical while agglomerators tend to be in the range of 30% to 50% \( N_c \), with larger units having lower values. In metric units [Perry 3]:

\[
N_c = \frac{42.3}{D^{0.5}} \text{ RPM}
\]

Critical speed is a method of normalising the different shell diameters to allow scale up and comparison.

8.2 Operating Speed

Operating speed is generally expressed as a fraction \( f \) of the critical speed. This allows comparison of the degree of ‘agitation’ in the agglomerator. Low \( f \) values have gentle rolling actions while higher \( f \) values have more tumbling and higher impact. Some industrial units of significant size have speeds in the region of 35% to 45% of critical [Bernard, Pyper and Pangbourne]. Other agglomeration operations for finer particulates use the higher end of the speed range [Perry 1]:

- Fertiliser (with a brittle powder) – 39%
- Iron Ore (which needs significant consolidation) – 51%

It has been shown by [Mishra] that a large increase in the application of interfacial energy (factor of times 3) has minimal impact on the size distribution of the agglomerates. However the work hardening (and breakage) of agglomerates is related to the power input. Thus for those feeds that need significant work hardening such as iron ore fines a higher operating speed (and power input) is indicated.

The ability to change the operating speed allows the agglomerating action to be changed. Addition of a variable speed drive can allow a significant degree of process control [Bernard]. A range of operating speeds is recommended for optimisation and throughput maximisation reasons. A minimum of \( No = 20\% N_c \) is recommended for solids transport through the agglomerator without build up of a deep bed at the feed end.

A median high speed selection for agglomeration of crushed ore is in the region of 47.5% \( N_c \). This can be subsequently adjusted to take account of the drive components selected and gear box ratios available.

8.3 Operating Angle

The operating angle is interconnected with speed, residence time and drum diameter and length selection. By using the model for the residence times the resultant operating angle can be computed. It will generally lie in the region of 1.5 degrees to 7.5 degrees.

This multi-variable parameter matrix does not yield a unique solution to the selection of the drum geometry and mechanical parameters. There is a wide range of latitude available to the engineer to optimise the design to suit other criteria specific to the particular project.
9. Power Draw

Shell power input is calculated on the basis of the torque arm to hold the burden and the offset angle and the maximum operating speed selected. The arrangement is shown in Figure 9-1.

- Figure 9-1 Power Draw Calculation Geometry

![Power Draw Calculation Geometry Diagram]

The geometry is relatively simple for the calculation of the segment centre of gravity and offset angle \( \alpha \). The burden mass is calculated from the solids operating volume and total (particle + fluid) burden bulk density. Power is calculated using the selected operating speed.

A further power allowance is made for accretion of material on the walls being carried to the top and then dropping off. The accretion thickness can vary and may have a significant influence on the total power required (particularly for smaller units). The proportion of accretion that dislodges is also variable with the stickiness of the agglomerates. The density used in the accretion calculation is the *agglomerate* density, as the accretion is at least this dense and likely to be greater.

The power draw is directly related to the operating speed through the torque x speed calculation; and indirectly through the change in burden dynamic angle of repose. As a result, the selection of the operating speed has a significant effect on the power input to the burden.
10. Motor Size

The motor size also needs to make allowance for the following:

- Shell rolling friction
- Internal viscous dissipation
- Mechanical drive train efficiency
- Electrical drive efficiency

Without specific knowledge of drive and dissipation issues it is generally good practice to allow for a total of 15% to 20% in the motor size for these items. Common efficiencies are:

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical drive</td>
<td>94%</td>
</tr>
<tr>
<td>Shell rolling</td>
<td>92%</td>
</tr>
<tr>
<td>Electrical conversion</td>
<td>95%</td>
</tr>
</tbody>
</table>

Nett for these three 82%
11. Model Verification

The model has been verified on a number of bases for the various components:

- Average total residence time criteria – from industry standard methodology.
- Shell power input – from verification against one large industrial installation.

The model outputs for the industrial verification trial [Miller] are summarised in Table 11-1 and Figure 11-1. These show good agreement between the power calculated from the model and that actually consumed in the field.

**Table 11-1 Power Draw Model Verification**

<table>
<thead>
<tr>
<th>Feed rate tph</th>
<th>1030</th>
<th>1180</th>
<th>1350</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Power Draw kW</td>
<td>95.4</td>
<td>97.3</td>
<td>102.7</td>
</tr>
<tr>
<td>Model Power draw kW</td>
<td>94.5</td>
<td>104</td>
<td>114</td>
</tr>
<tr>
<td>Percent full</td>
<td>13.6</td>
<td>15.5</td>
<td>17.8</td>
</tr>
</tbody>
</table>

*Model Parameters*

- Accretion thickness: 25mm
- Accretion drop off: 50%
- Residence time seconds: 30
- Dry bulk density: 1.6 t/m$^3$
- Wet burden density: 1.744 t/m$^3$ (9% moisture)
- Drum Diameter m: 2.3
- Drum Length m: 10
- Operating Speed RPM: 12.5
- Speed % Critical: 44.8%
- Total drive efficiency: 80% (motor 95%, drive train 92% - chain drive, rolling friction 94%)

The low increase in actual power draw as the throughput increases is an indication of an increased amount of slip and bypassing that is occurring with the rise in the fill proportion. Evidence that this was occurring was a drop off in the quality of the agglomerates; which showed lower density as a result of less compaction and consolidation.
These results provide confirmation that the model has the ability to predict the power draw with an accuracy acceptable for design purposes. The agreement between the present model and field results allows it to be used with some confidence. The field results also indicate that a 15% fill is a practical limit to this particular drum capability, before significant slip occurs and reduced quality agglomerates are produced.

The intersection of the field and model power draw curves is at approximately 12% fill. This correlates very nicely with the ‘normal’ design criteria of 12% to 13% fill recommended as the maximum for design purposes [Perry 3]. The confirmation of this maximum from industrial scale data is good validation of the recommendation.

**Figure 11-1 Capacity and Power Verification**
12. Detailed Design Issues

12.1 Mechanical

12.1.1 Support

The support for the agglomerator needs to take into account the offset load mass that is created during operation. Figure 12-1 illustrates the large difference between the high side load and the low side load. This aspect is particularly important when friction drive systems such as rubber tyres are used.

![Figure 12-1 Illustration of Offset Load Profile in an Agglomerator](image)

12.1.2 Feed Chute

The feed needs to be angled to the side, in such a way that the discharge is into the deepest part of the running load. In other words it should be angled to delivery at approximately 35 degrees to the vertical. Figure 12-1 shows the problem with a straight feed chute delivering onto a very thin bed of material.

12.1.3 Lining

The drum shell needs to be lined to protect it from abrasion and more particularly corrosion (for copper systems) from the sulphuric acid and the Cu ->Fe cementation reaction. Due to the extremely rapid Cu ->Fe reaction, the risk of soluble Cu contacting the shell must be minimised by all means possible. For this reason bolted liner systems are not acceptable and a fully bonded liner system needs to be used.
Figure 12-2 shows a typical drum with bonded liners and lifters (together with a back-plate for spillage control).

The integrity of the lining needs to be ensured throughout the design and selection process. If the drum is manufactured in flanged sections, then the liner is bonded after the flanges are bolted together; to bridge the gap between the sections. Relying on a gasket or other sealing method, entails risks of the Cu solution "wicking" into the flanges and reducing the structural integrity of the unit.

Nitrile rubber is recommended when using solvent extraction (SX) raffinate as this material is resistant to the solvent extraction organic that is entrained in the stream.

12.1.4 Spillage Control
This area is often subjective but the main potential spillage will occur at the feed end. This will require a partial end plate to avoid excessive spillage at this end.

The discharge chute will need to be adequately sized to collect the agglomerates, as well as allow for the variable drum angle. A fume/steam control curtain/cover can also be incorporated. Since the agglomerates are by definition at their maximum sticky point, the discharge chute must be designed to prevent build up and blockage. Material testing is necessary to determine minimum chute angles.

12.1.5 Angle Adjustment
Adjustment is readily done by pinning the feed end and having the discharge end sit on a pin rack (or a pair of Vernier drilled bolting plates) with pin location. Actual adjustment is made with portable hydraulic lift jacks. The agglomerator sub-frame is bolted once the required angle is obtained.

12.1.6 Speed Adjustment
A method of speed adjustment is required. This may take the form of:
- VVVF drive
Hydraulic drives
Vee belt step wise adjustment
Chain drive step wise sprocket change

Except for conditions requiring continuous adjustment, either of the latter two systems is appropriate. For small drive sizes (<150 kW) the VVVF option is likely to be the most cost effective.

12.1.7 Control of Accretion Build-Up

The action of agglomeration will create a sticky material; which will adhere to the walls of the drum. This will build up and could eventually overload the drum. Traditional practice in iron ore agglomeration is to have a counter-rotating cutter bar to remove the build-ups. In acidic environments this option is not appropriate. Other methods have been developed. These include:

- A loose or floppy liner which is secured at 4 or 6 points on the circumference and allowed to flop downwards at the top of the cycle.
- Loose flaps which are fixed at the leading edge only. These also fall downwards at the top of the cycle, releasing the build up. Either method would be appropriate if installed over the top of a bonded liner.

12.2 Process

12.2.1 Water Addition

Chilean copper practice is to add water and mix with the ore prior to acid addition. This allows the acid to mix with the water; whereas the acid tends not to mix well with the ore alone due to density, viscosity and surface tension affects.

Water addition can be done in the feed chute (if suitably lined) or just inside the drum at the feed end. Further water additions should be done in the toe of the burden to allow best mixing with the ore. As discussed earlier this seems to provide the best use of the water in agglomeration as it is added at the most active part of the burden mass.

The water for wetting of sulphide ores should be solvent free ILS solution. This has no SX organic (which would need nitrile rubber liners for protection). It also contains significant biomass (approximately 10^7 /ml) for initiation of the bioleach chemistry.

12.2.2 Acid Addition

Acid is added after the water, approximately 1-1.5m inside the drum. This allows the water and ore to be well mixed prior to acid addition. It also is a safer operation with the acid further away from the operators. Addition is made onto an established bed of material, which tends to protect the rubber lining from concentrated acid.

A further benefit of acid addition after the initial agglomerates have formed is the use of this outside on the outside of the agglomerates. The silicate (or gypsum) bridges that are formed help to provide agglomerate strength and longevity under the leaching conditions. By proper selection of the acid addition point considerable changes to the agglomerate quality can be made.

12.2.3 Heat Rise

Using an approximate value of 0.166 cal/g/°C for the ore specific heat, the temperature rise from the heat of acid dilution is:
19°C for 30 kg/t acid into 10% water in the ore

For a starting ore temperature of 30°C this gives a final average temperature of 50°C for the agglomerated ore. Surface temperature of the newly acidified particle will be higher, with surface temperatures at the point of acid addition close to 90°C.

The average ore temperature is ideal for bacterial growth and should be retained for as long as possible. However the temperatures are high enough that care needs to be taken with the drum wear and corrosion liner selection.

12.2.4 Controls

Controls are relatively simple with both ILS and acid added on a ratio basis to the feed tonnage. The ratio set point is adjusted by the operator; from results of testing the agglomerate quality. Unless the ore characteristics are changing significantly the ratio does not change by a large amount. However if the ore has varying proportions of clay then the ratio can change quite appreciably. Even a small amount of clay can have a large effect on the moisture holding capacity and the sticky limit of the material [Fernandez].

Cerro Verde in Peru have developed a method of controlling the agglomeration water addition via a conductivity measurement of the discharged agglomerate stream [Fernandez]. This method holds great promise for the on line control of moisture addition to achieve the required degree of agglomeration. The conductivity can be cascaded with the tonnage related moisture addition rate to trim to the moisture addition ratio to achieve good agglomeration.

Safety reasons require feed tonnage measurement. This allows the acid to be stopped for any feed interruption; thus protecting the rubber lining from direct acid addition.
13. Conclusions and Recommendations

The model developed by for drum agglomeration allows selection of geometry and power input. Specific aspects considered are:

- Calculation of total operating volume
- Solids residence time based on operating volume
- Solids residence time based on geometry and mechanical set up parameters.
- Selection of the drum aspect ratio.
- Alteration of operating fill to allow for smaller or larger feed openings
- Selection of proportion of critical speed
- Calculation of shell and motor power requirements.

The model uses solids total residence time to calculate the required operating volume. The burden density is calculated from the solids bulk density and the fluid density. Power is calculated using the Liddell and Moys correlations for burden position and shape, and the operating drum speed. A further power allowance is made to allow accretion drop off during drum rotation.

Results from the model (especially power) have been verified from industrial installations of significant size. Predicted and observed power draws are within 5% when burden slip and bypassing is not significant. When these are significant (at higher fill percentages >15%) the actual power draw will be less than the model prediction.
14. Nomenclature

A angle of repose
a,b,c constants
Br Brodenstein Number = D/UL
Cd Discharge Coefficient
D shell internal diameter m
f fraction of critical speed
H weir depth
L shell internal length m
Nc critical speed RPM
No operating speed RPM
Q total solids flow rate m³/h
S operation slope m/m
T solids feed rate tph
U agglomerator axial velocity in Brodenstein number
w moisture percentage w/w in agglomerated material

\( \alpha \) burden dynamic angle of repose
\( \alpha' \) burden dynamic angle of repose with drum angle included.
\( \beta \) drum operating angle = \( \tan^{-1} S \)
\( \varepsilon_p \) particle volume fraction
\( \theta \) burden subtended angle
\( \rho_b \) bulk density
\( \rho_f \) fluid density
\( \rho_p \) particle density
\( \phi \) average residence time minutes
15. References


Levenspiel O “The Chemical Reactor Omnibook”, Oregon State University, 1993, p64.11


