Drum Scrubber Design and Selection

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ABSTRACT

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

- Calculation of total static and operating volumes.
- Total residence time based on total operating volume.
- Solids residence time based on solids operating volume.
- Selection of the 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 either solids or total residence time to calculate the required operating volume. The solids residence time is based on the proportion of coarse solids in the feed. Material finer than the reject size is considered as part of the slurry. The solids operating volume is the static volume plus the surcharge on the discharge weir required for flow of the solids from the unit. The total operating volume is the static volume plus the surcharge on the discharge weir for the total flow to exit the scrubber. The burden density is calculated from the coarse solids bulk density and the slurry density that includes all the fine solids. Power is calculated using the Liddell and Moys correlations for burden position and shape, and the operating rotational speed.

Results from the model (especially power) have been verified from industrial installations of significant size. Predicted and observed power draws are within two per cent. A check against the JKMRC mill model shows power draw prediction agreement to within four per cent.

INTRODUCTION

The design and selection of drum scrubbers is an inexact science at best with little published data on selection criteria or calculation procedure. To date most scrubbers have been selected on simple criteria such as global slurry residence time rather than more rigorous criteria such as ‘solids’ residence time or degree of attrition. Some models have been attempted by research organisations such as JKMRC to consider the degree of attrition question but they have not been released into the public domain (Napier-Munn, 2003; Valery, 2003).

The drum scrubber model described in this paper considers the physical selection of the scrubber geometry and its drive power. It is based on testwork results that define the residence time necessary to provide the required degree of attrition. In most cases these will be 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. The solids residence time
is obtainable directly from the batch test or by back calculation from the model for a continuous test. In either case the continuous flow scrubber needs to be selected to achieve the necessary solids residence time.

A two component model is used for calculation of the residence time. A coarse solids fraction and a fine solids fraction are considered. The coarse fraction is the material of interest in terms of the scrubbing residence time while the fine fraction is assumed to be part of the fluid (slurry) flow and to have a different residence time. In general a split size of 0.3 mm to 0.5 mm is used to differentiate the coarse/fine differentiation. The split size selection is application specific and can be related to the economic cut-off (bauxite +0.3 mm or diamonds of +0.5 mm) or to a more fundamental knowledge of the settling characteristics of the solids and the size below which slurry behaviour can be assumed in the scrubber.

The model is set out in a number of sections that each calculate some aspect of the scrubber or scrubbing activity. These sub models are discussed in detail in the following sections. A validation has also been made on the overall model result to check the calculated power against the model. It has not yet been possible to validate the model against more fundamental data as to:

- The applicability of the approach used (coarse/fine solids).
- The focus on solids residence time.

**RESIDENCE TIMES**

**Solids Residence Time**

The coarse/fine solids model is used to separate the scrubbed solids from the slurry of attrited fines that act in the fluid phase. In reality there will be a residence time distribution function for all solids of varying size and mobility (Hutton, 2003). This distribution function can be very close to plug flow, even for long units such as rotary kilns (Ang, Tade and Sai, 1998; Sai et al, 1990). The approach adopted is a simple plug flow model assuming total radial mixing and no axial dispersion. At present there is no information included on a potential residence time distribution of either the solids or the fluid (slurry). 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 the coarse material occupying a volume set by the bulk density of the coarse solids. This needs to be differentiated from the total bulk density, which includes the fines. Values of the volume fraction of solids in the scrubber will vary from the minimum body-centered-cubic mono sphere of 0.52 (=π/6) to as high as 0.68 for a wider range of particle sizes but which have a limited bottom size.

\[ \rho_b = \varepsilon_p \rho_p \]

The volume occupied by the solids is the ‘struck’ volume of the scrubber (set by the diameters of the scrubber and the outflow weir) plus the solids surcharge set by the volumetric flow of the solids over the circular outflow weir. This second volume is not often taken into account when comparing or calculating scrubber residence times. It can be a very significant part of both the slurry and of the solids volume. The method adopted is a
simplification of the real situation but does allow comparison of alternate geometric ratios between pilot and commercial units.

The volumetric flow rate of the solids and the scrubber operating solids volume provides the solids average residence time.

**Slurry Residence Time**
The slurry is assumed to be of a composition set by the flow rate of feed solution and the fine solids in the feed. The volumetric flow rate is the total of the solution + fine solids. The volume that it occupies is calculated from:

Total scrubber operating volume minus coarse solids particle volume

The assumption in this analysis is that the slurry fills all the voids in the coarse solids burden as part of the active slurry volume. The burden slurry is assumed to be 100 per cent ‘active’ rather than partially ‘static’. This assumption leads to potentially higher estimates of slurry residence time than might be achieved in practice with a less mobile burden slurry.

The total operating volume is set by the total feed (= outflow volume) and the diameter of the circular outflow weir. The height of the weir necessary to pass the flow is calculated as described later. From these two variables the slurry (or liquid) average residence time can be calculated. The geometry for the scrubber residence time model is shown in Figure 1.

![FIG 1 - Scrubber Residence Time Geometry Model.](image-url)
Overall Residence Time
The overall average residence time is calculated from the total feed volume and the total operating volume. This tends to be the global parameter that most practitioners use. Care needs to be taken with batch test interpretation that the selected overall residence time does not overly increase the solids residence time. Batch testing *inter alia* has the same residence times for the solids, the liquid and overall. A continuous scrubber will generally provide the following ratios:

<table>
<thead>
<tr>
<th>Residence Time</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average residence</td>
<td>1.0</td>
</tr>
<tr>
<td>Solids residence</td>
<td>2.5 x average</td>
</tr>
<tr>
<td>Liquid residence</td>
<td>0.67 x average</td>
</tr>
</tbody>
</table>

It is evident that selection (based on batch testing) on overall average residence time alone can significantly bias the selection process and lead to either over design or over-scrubbing and loss of potential product; from a unit where the solids residence time is far too long.

This is an aspect of commercial units that have been selected on the basis of batch testing. One large diamond plant installed scrubbers for a nominal 1 minute residence time at 300 tph. The units are presently treating 800 tph with a solids residence time of 0.75 minutes. In this instance the scrubber is running at high proportions of critical speed = 80 per cent Nc with a consequent high specific energy input. The scrubbed material meets the process needs at the shorter residence time probably due to higher energy input (kWh/t) than the testing unit. This aspect is discussed later.

**SCRUBBER GEOMETRIC CONSIDERATIONS**

Shell Aspect Ratio
The aspect ratio of the drum (L/D) is generally kept in the region of 2:1. However longer and 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 2.5: with a preponderance around 2:1. One of the drivers of shorter scrubbers is the diameter of the feed opening as discussed later. With larger feed particles requiring large feed openings the diameter of the unit gets larger for a given total residence time volume(s). As a result scrubbers for primary crushed and unscreened material tend to be shorter than for feeds with a constrained top size (say from a secondary crushed or screened material). For the L/D parameter there are no set values. The actual geometry is at the control of the design engineer.

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 operating level in the unit to minimise splash and spillage from the feed end. As a result the calculations of the scrubber operating volume (and weir surcharge height) need to be part of the overall selection of the feed diameter.

One of the assumptions made in the modelling process is that there is little or no hydraulic gradient from one end of the scrubber to the other. This is a simplification of the real situation where there is likely to be a solids top surface gradient but the slurry gradient will be minimal. The low slurry surface gradient is a result of the generally very wide flow ‘channel’ within the scrubber and the low hydraulic head required to create the flow from one end to the other. This is less than a few millimetres and is often ‘submerged’ in the surface turbulence, which can be one or two orders of magnitude greater.
**Struck Volume**

The struck volume is the static volume of the scrubber at rest. It is set only by the length, diameter and outflow weir diameter, and relates the area of the circular segment tangential to the outflow weir invert. Values of the proportional struck volume range up to 25 per cent. The higher values can only be utilised when a small feed spout is suitable. In general the maximum that can be used for larger feed spouts is 20 to 22 per cent as a first approximation.

The weir:drum diameter ratio for 25 per cent struck volume is 0.40 while for 20 per cent it rises to 0.5. The diameter ratios are also drum diameter dependant and should be calculated as such for each application.

**BURDEN DENSITY**

The burden density is calculated from the combination of the solids bulk density and the slurry density filling the voids in the burden.

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

It will be higher than the full size distribution bulk density by inclusion of the fluid density in the solids voids. It is somewhat conservative as it assumes no reduction in burden density due to the action of the drum rotation. This is appropriate with the low percentage of critical speed that scrubbers operate. The action of the burden mass is one of tumbling rather than cascading and little change in charge density is observed until cascading is evident (Liddell and Moys, 1998).

**OVERFLOW HEIGHTS**

The height of the flow over the circular discharge weir has been an issue for calculation for a number of years. It is a common situation in gravity flow situations but has not been addressed by standard texts on hydraulics. Analytical analysis of the situation shows that there is a resultant integral that is not amenable to resolution other than by numerical integration. A numerical solution to the integral has been obtained and a simplification for engineering use determined (Miller and Newton, 2000).

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.

\[
Q = C_d a D_0^b H_{\text{tot}}^c
\]

Appropriate values of a, b and c agree with the numerical integration solutions with errors of less than 1.6 per cent for \(H_{\text{tot}}<D_0/3\). 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 slightly more than for a sharp edged weir when the more tapered shape of the actual discharge is considered. The circular weir correlations developed by Wemco for their heavy medium baths 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.
One other aspect to consider when calculating the discharge depth is to ensure that the total depth at the centre is sufficient to provide an unhindered flow path for the maximum particle size. A recommendation of $1.1 \times$ maximum size is common for heavy medium baths and is used in the model as a check.

**BURDEN POSITION**

The burden shape is modelled by the circular segment that corresponds to the outflow weir solids operating height. This is confirmed by Liddell and Moys, as one of the most appropriate methods of determining ‘mill’ power. In essence the scrubber is a medium sized, low solids density, low speed fully autogenous mill with high throughput rates. The size of the segment is set by the scrubber geometry (shell and outflow diameter) and the solids feed rate and bulk density (operating weir height). The only other parameter required for the calculation of the power draw is the angular position of the burden.

Liddell and Moys have provided a relation between the dynamic angle of repose of the burden with drum rotational critical speed. This is illustrated in Figure 2. This allows the calculation of the angular offset of the burden, which is used in the power calculation.

![Figure 2 - Burden Dynamic Angle of Repose.](image)

The actual positions of the operating burden and water/slurry are shown in Figure 3. The burden is offset to achieve the dynamic angle of repose but the overall slurry level is assumed to be horizontal.
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 attrition rather than particle breakage are the normal scrubbing actions, the operating speed is generally much less than for mills. Mills operate in the range of 70 to 75 per cent of critical while scrubbers tend to be in the range of 30 to 65 per cent $N_c$, with larger units having lower values.

$$N_c = \frac{42.3}{D_s^{0.5}} \text{ RPM}$$

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

OPERATING SPEED

Operating speed selection can be modified by the arguments regarding power scale up issues discussed below.

A range of operating speeds is recommended for optimisation and throughput maximisation reasons. A minimum of $N_o = 30$ per cent $N_c$ is recommended for solids transport through the scrubber without build up of a beach at the feed end.

POWER DRAW

Shell power input is calculated on the basis of the torque arm to hold the burden at the offset angle and the operating speed selected. The arrangement is shown in Figure 4.
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 + slurry) density. Power is calculated using the mill selected operating speed.

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.

**MOTOR SIZE**

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

- Shell rolling friction.
- Internal vicious 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 per cent in the motor size for these items. Common efficiencies are:

- Mechanical drive 94 per cent
- Shell rolling 95 per cent
- Electrical conversion 96 per cent

Nett for these three is 85.6 per cent or a friction loss factor of 1.17. This compares with a similar factor for 1.26 used in recent FEM modelling (Djordjevic, 2003).
POWER SCALE UP

One of the more significant issues in selection of the critical speed is the total energy input to the solids. The scrubber is acting as a light autogenous mill and mill selection criteria can become important, particularly when power input is greater than 0.5 kWh/t (David, 2003). Under these circumstances it is important to consider the kW/t of coarse ore as a scaling factor in the capacity of a scrubber. Once the total energy input kW/t becomes significantly larger than the pilot or batch test there is a cogent argument for reverting to comminution criteria (David, 2003).

It has been suggested (David, 2003) that the scrubbing activity is a sequence of low to higher power actions that tend to be sequential in nature. The three main stages are:

1. Wetting of the fine material below discard size.
2. Dispersion of ‘loosely’ agglomerated materials to release material below the discard size.
3. True size reduction of material coarser than the discard size through energy input and attrition/comminution.

The time for stage 1 tends to be short unless any clay materials are compacted and constrained by physical particle effects (such as for kaolin dispersion). Stage 2 is a significant time dependant parameter but is also influenced by the energy input in the dispersion process. Blunging of clay materials is a specific use of high energy input to gain dispersion in a short time.

Stage 3 is truly energy input dependent with the creation of new surface (= particle breakage or attrition) directly related to specific energy input.

From this discussion it appears that there is an interaction between residence time and specific energy input, that will set the capacity of a particular scrubber.

As noted earlier there is industrial experience to suggest that specific power input can be the correct scaling method for large units. For specific power inputs of 0.5 kW/t or larger, the solids residence time criteria can be modified by the unit specific energy ratio. In this situation the solids residence time can be reduced (=increased throughput) to allow the specific coarse ore kWh/t power to reduce towards that found to be effective in the pilot or batch testing.

From these discussions it is reasonable to scale up (particularly large scrubbers) on the basis of solids residence time and then to modify the residence time requirement by the ratio of the specific energy input between the testing system and the proposed industrial scale unit.

MODEL VERIFICATION

The model has been verified by a number of methods for the various components:

- Operating circular weir height correlation - from published Wemco data
- Average total residence time criteria - from industry standard methodology
- Average solids residence time criteria - from discussion with recognised authorities and industrial experience
- Shell power input - from verification against two large industrial scrubber installations and against the JKMRC autogenous mill model.
The model outputs for the industrial verification trials are provided in Table 1. These show good agreement between the power calculated from the model and that actually consumed in the field.

An alternate model for autogenous milling from the JKMRC, was used to calculate the power draw for an installation that was also modelled by the present procedure. Again the two models produce very similar estimates of the burden density and the shell power draw.

### Table 1 - Power Draw Model Verification.

<table>
<thead>
<tr>
<th>Installation</th>
<th>Unit</th>
<th>Iron Ore</th>
<th>Diamonds</th>
<th>Bauxite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model power</td>
<td>kW</td>
<td>166</td>
<td>357</td>
<td>519</td>
</tr>
<tr>
<td>Consumed power</td>
<td>kW</td>
<td>162</td>
<td>364</td>
<td>-</td>
</tr>
<tr>
<td>JKMRC model</td>
<td>kW</td>
<td>-</td>
<td>-</td>
<td>502</td>
</tr>
<tr>
<td>Charge density</td>
<td>t/m³</td>
<td>1.968</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge density JKMRC</td>
<td>t/m³</td>
<td>1.97</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These results provide a large degree of confidence that the model has the ability to predict the power draw with a degree of accuracy acceptable for design purposes. The agreement between the present model and field results, as well as with the respected JKMRC mill model, allows it to be used with confidence.

**CONCLUSIONS AND RECOMMENDATIONS**

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

- Calculation of total static and operating volumes.
- Total residence time based on total operating volume.
- Solids residence time based on solids operating volume.
- Selection of the aspect ratio.
- Alteration of operating fill to allow for smaller or larger feed openings.
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Results from the model (especially power) have been verified from industrial installations of significant size. Predicted and observed power draws are within two per cent. A check against the JKMRC mill model shows agreement to within four per cent.
ACKNOWLEDGEMENTS

It is with thanks to the various operating companies who have made their operating data available. Without this sort of feed back the technology does not advance nearly as quickly.

NOMENCLATURE

Cd       weir discharge coefficient
CG      centre of gravity of the burden
Ds      shell internal diameter m
Do      weir outlet diameter m
h       burden toe to toe operating lift
Hs      weir solids discharge depth m
Htot    weir invert total discharge depth m
Nc      critical speed RPM
No      operating speed RPM
Q       total flow rate m³/h
rm      radius of ‘mill’
α       burden angle of dynamic repose
θ       burden sector subtended angle
εp      particle volume fraction
ρb      bulk density
ρf      fluid density
ρp      particle density

REFERENCES


David, D, 2003. Personal communication.


