Essential Readings in Light Metals: Alumina and Bauxite.
Edited by Don Donaldson and Benny E. Raahauge.

MIXER DESIGN OPTIMIZATION FOR HIGH SOLIDS CONTENTS MEDIA : METHODOLOGY AND APPLICATION TO THE PECHINEY'S HIGH DENSITY PREDESILICATION PROCESS

[1]ROBIN INDUSTRIES, Florent BOUQUET[1]
[1]ROBIN INDUSTRIES ; 10 rue du Bois Gasseau , BP94 Samoreau ; 77212 AVON cedex , FRANCE

Abstract

The most obvious aim of a mixer in slurries exhibiting high solids concentrations is to prevent solids from settling at the bottom of the tank.

Nevertheless, depending on process requirements, the mixer may also be able to keep the solids concentration homogeneous all over the height of the tank, to prevent short-circuits in the tank, to facilitate the slurry transfer from one tank to another in case of continuous processes, to achieve sufficient heat transfer performances. The list is quite long.

This paper points out the important parameters to take into account for the mixer design and presents a methodology for defining an optimized mixing system for high solid contents slurries.

An application of this method to PECHINEY's high density predesilication process will be described for process capacities up to 1000 m^3.

Introduction

A great number of papers dealing with solids suspension are available since more than 50 years. Most of the time, they describe many methods to predict just off-bottom solids suspension speed (Njs: Zwietering (1) correlation) including many parameters such as the type of impeller used or the geometric parameters of the system.

Unfortunately, even if this calculation method sounds right when considering low viscosity Newtonian rheologies, it is more difficult to obtain information for more complicated cases.

This paper will deal with a method to design a mixer depending on what the process requires including practical views on how to cope with operational elements such as slurry transfer and restarting of the agitator after shut-down.

Rheological characterization of the slurry

The rheological properties of a slurry evolve along with solids concentration. For example, with 20% w/w of phosphate solids in water, dynamic viscosity may be as low as 5.10^{-3} Pa.S whereas with 68% solids, it may grow up to 5 Pa.S in industrial conditions around the impeller.

In a phosphate storage tank with 68% w/w solids, the agitator has to prevent dead zones from appearing in the tank which automatically imply that solids have to be homogeneously distributed all over the height of the tank. The aim of the agitator in this case is to agitate a viscous media rather than achieving conventional solids suspension.

Consequently, the rheology of the slurry is the first parameter to take into account and may be the main criteria that will decide the way to design the right agitator.

Rheology : fundamentals
For fluids undergoing laminar shear, the resistance deformation depends on the dynamic viscosity. For a linear velocity gradient arising due to the movement of one parallel plate over another, the relationship between shear rate γ and the shear stress τ, is given by :

$$\tau=\mu.\gamma$$

Newtonian fluids
For Newtonian fluids, μ does not depend on shear rate. This behaviour corresponds most of the time to low solids contents slurries (<40% w/w).

Pseudoplastics or shear thinning fluids

$$\mu_a=K.\gamma^{n-1}$$

n = flow behaviour index
K = consistency index
Generally, with common slurries, 0<n<1, which means that the apparent viscosity decrease along with shear rate (ex: CaCO$_3$ slurries up to 80% solids).

Plastic fluids

$$\tau=\tau_y+\mu.\gamma$$

These materials are characterized by a yield stress. In these cases, a minimum stress is required to break down the media structure sufficiently before any movement will occur (ex: red mud at high concentrations in alumina refineries).

Plastic fluids with shear thinning

$$\tau=\tau_y+K.\gamma^{n-1} \quad \text{Herschel-Buckley model}$$

This case is common (Bauxite from Weipa, phosphate slurries, magnetite, etc.) and is the hardest case to cope with.

In addition, with thixotropic fluids, the apparent viscosity reduces with time as the material is sheared at a constant shear rate.

It is clear that, depending on the rheological behavior of the slurry, the design method will not be the same.

Mixer design for solids suspension / low viscosities

The principal method widely used is the Zwietering's correlation, which purpose is to determine the just-off bottom solids suspension speed.

$$N_{js}=\frac{S.\upsilon^{0.1}.d^{0.2}\left(g\frac{\Delta\rho}{\rho_l}\right)^{0.45}X^{0.13}}{D_m^{0.85}}$$

J.Wu, Y.Zhu and L.Pullum (2) have shown that there was a link between the impeller capacity and the S parameter in this correlation that can be expressed as

$$N_q.S=K_z$$

where Nq is the impeller flow number and K_z is a non-dimensional constant independent of the solid-liquid material property and impeller geometry. See Table I for data dealing with different impellers used in solids suspension. Empirical data on S and its variation with impeller/tank geometry has been given by Nienow (3) amongst many others.

TABLE I
Impeller specification, flow number, power number and S parameter,
$C/T = 1/3$, $D_m/T = 0.41$, $T = 0.41m$

Impeller	Full name	Flow pattern	Number Of Blades	Blade Width W/D	Flow Number Nq	Power Number P_0	$\frac{S}{S_{45PBT4}}$
HPM 20 3	Robin Industries Propeller	Axial	3	NA	0.66	0.41	1.15
HPM 10 3	Robin Industries Propeller	Axial	3	NA	0.48	0.221	1.58
31 T	Robin Industries Propeller	Axial	3	NA	0.37	0.11	2.05
30PBT4	30° pitched 4-bladed Turbine	Axial radial	4	1/5	0.58	0.56	1.31
45PBT4	45° pitched 4-bladed Turbine	Axial Radial	4	1/5	0.76	1.22	1.00

From this table, for a given slurry, at constant geometric parameters (D_m/T, C/T, H/T), the power needed by an HPM 20 3 is far less to achieve solids suspension compared to 45PBT4 which needs +100% more power for the same result.

<u>Geometry optimization of the mixer</u>

In order to achieve full solids suspension, depending on H/T ratios, the number of impellers on the agitator shaft may increase. For instance, when H/T < 1, a single propeller may be enough to cope with uniform solids suspension. When H/T >1, in case of a single impeller configuration, there is a two circulation loops system that appears in the tank (see Figure 1). In this case, if the velocities in the upper circulation loop are too low to keep solids in suspension, there will be a large solids concentration gradient along with vessel height.

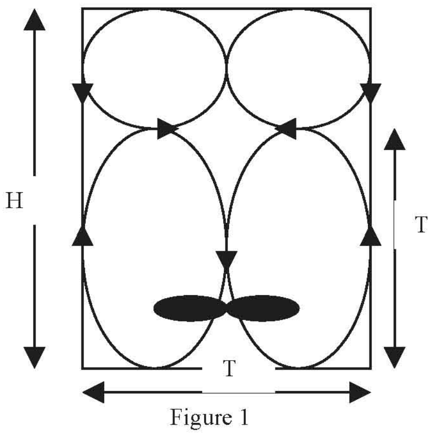

Figure 1

It is important to note that the loops in the vessel may be different from what is described in Figure 1 when slurry is fed by the top engendering a modification of velocity fields with a positive effect.

Practically, in order to limit the power needed for full solids suspension, it is necessary to have at least one more impeller per cylindrical part of the vessel which height is equal to T (see Figure 2).

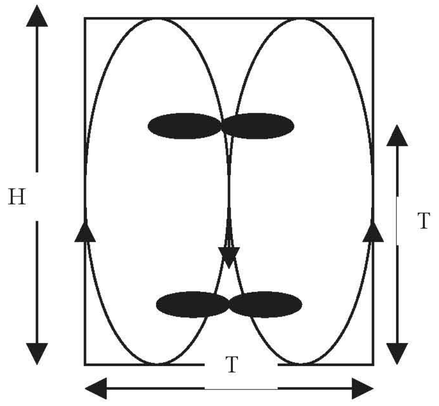

Figure 2

Inlet-outlet design

The way the slurry leaves the vessel will determine how to define the mixer:

Outlet by pump at the bottom of the vessel

- single impeller : no homogeneity required
- multiple impellers : depending on the shape of the vessel and the homogeneity needed

Advantage: there is less risk to accumulate large solids particles in the vessel.
Drawback: use of a pump (investment + operating costs)

Simple overflow

- single or multiple impeller configurations depending on the vessel height to diameter ratio
- perfect homogeneity needed. For long residence time, the liquid height in the overflow may be very small compared to the other dimensions on the vessel. In this case, there is a great risk for solids to accumulate in the tank as there are always less solids contained near the liquid surface due to a layer effect. To prevent such a situation, the dimensions of the outlet have to be calculated so as to assure a sufficient velocity in this area.

Advantage: low cost / easy to install
Drawback: great risk for solids accumulation

dip pipe outlet

- single or multiple impellers depending on the shape of the vessel. For high solids concentration media, homogeneity is required so as to limit specific gravity differences between the top and the bottom of the tank which could cause direct overflow of the vessel content in the outlet pipe.
- The upward velocity in the pipe has to be as high as possible so as to prevent solids from settling in it. (ex : 0.7 to 1 m/s in alumina precipitators)

Advantage : as for the outlet by pumping, there is less risk to accumulate large solids particles in the vessel.
Drawback : only non-fouling products can be handled by such a method. Use of an airlift in the pipe may be needed to control differences between the level of the slurry in the vessel and the level in the outlet pipe to prevent direct overflow. Visual or automatic control is important to check the smooth running of this system.

Comparison between overflow and dip pipe

To compare simple overflow outlet to dip pipe outlet, a test has been done in a 2 m^3 vessel initially filled with water and a known quantity of solids. The mixer rotational speed has been set visually so as to have complete homogeneity in the vessel. At t = 0h, a known continuous flow rate (1.7 m^3/h) of water is introduced in the vessel. The liquid + solids flowrate coming out of the vessel is filtered and solids are counted.

Three tests have been done :

- Power = 100 % + outlet by simple overflow
- Power = 100 % + outlet trough a dip pipe (upward velocity in the pipe = 1 m/s)
- Power = 300 % (increase of initial speed by 43%) + outlet by simple overflow

The results of the amount of solids filtered along with time for these three tests have been compared to the theoretical values (assuming there is no solids accumulation in the vessel) (see Figure 3).

From the results, it is obvious that the configuration using the dip pipe is far more efficient in terms of efficiency to extract solids from the vessel compared to simple overflow.

Moreover, even by increasing the rotational speed by 43% (300% of initial power), there were still bad performances of the configuration using the simple overflow compared to the test with lower rotational speed using the dip pipe.

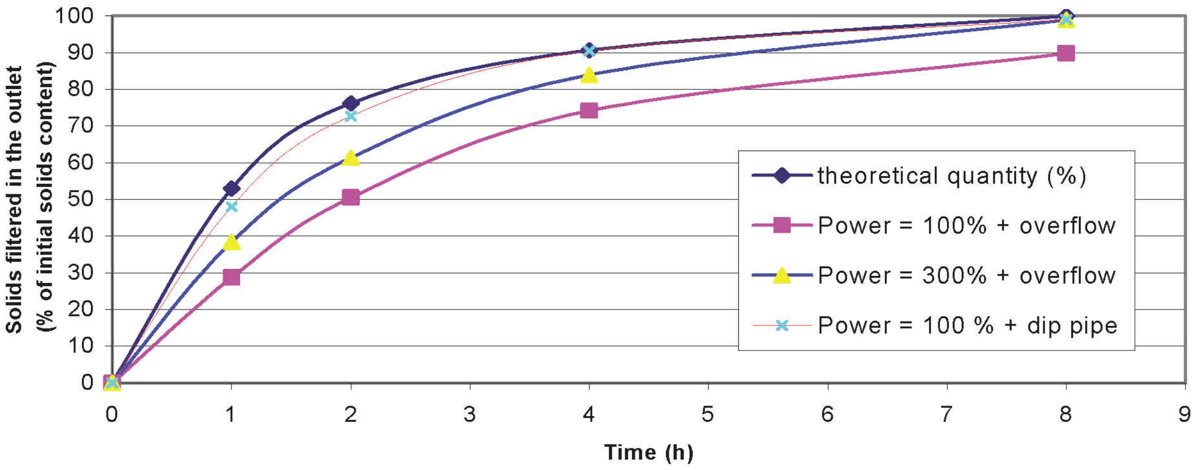

Figure 3

Mixer design for solids suspension / Shear thinning + plastic fluids

Effect of viscosity on solid suspension

The reduction of Reynolds number below 300 in a stirred vessel suppresses partially the axial component in the discharge of axial and mixed-flow impellers. In this case, the overall pattern of these impellers is then comparable to the one of a radial impeller. The consequence is that the optimum D_m/T in this case increases from .35 in water-like viscosity to around .5 in this range of Reynolds number. It must be noted that Zwietering's correlation and corresponding S parameter is not valid anymore in this Reynolds range.

M.Zirnsak and D.Stegink (4) highlighted in their paper the main problem that may be encountered with shear thinning slurries in predesilication tanks (Eurallumina refinery /Italy):

- build-up of thick slurry in the tank up to the whole volume

K.Wichterle and O.Wein (5) have investigated the origin of such a media behavior pointing out what is called the "cavern theory" using X-ray flow visualization technique with xanthan gum solutions (yield stress from 5.8 to 14.2 Pa).

With shear thinning fluids, high apparent viscosities are observed in low-shear areas. Consequently, because of a high resistance to fluid motion, poor mixing may occur.

With a yield stress, the phenomenon has greatest effects: a cavern is formed around the impeller outside of which the media is stagnant (see Figure 4). In this case, the shear stress engendered by the impeller is lower than the yield stress of the slurry in the outer area of the cavern leading, most of the time, to fast build-up in the tank.

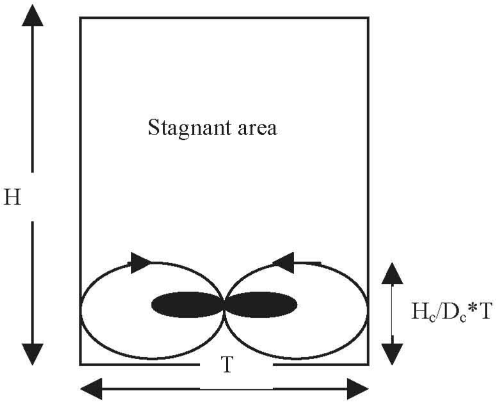

Figure 4

In the transitional flow regime (between turbulent and laminar), the cavern size may be represented by a cylinder (diameter = D_c), which height (H_c) may be different depending on the type of impeller used (Elson(6)):

- H_c/D_c= .4 for disc turbines
- H_c/D_c= .45 for two blades paddles
- H_c/D_c= .55 for pitched blades turbines/ propellers

A model have been developed using the Yield stress Reynolds number:

$$\mathrm{Re}_y = \frac{\rho . N^2 D_m^2}{\tau_y}$$

which can be written: $\left(\frac{D_c}{D_m}\right)^3 \alpha\, P_0\, \mathrm{Re}_y$

For a given vessel, with a constant D_m, it means that:

$$P\ \alpha\ \tau_y^{3/2}$$

When the yield stress is multiplied by 2, the power needed to reach the wall of the vessel is multiplied by around 2.8.
Once the cavern has reached the vessel wall,

$$H_c\ \alpha\ N^{0.87}$$

With pseudoplastic fluids, there is also a highly mixed pseudo-cavern surrounding the impeller which itself is surrounded by relatively slow moving fluid. An analogy can be made between τ_y and the minimum shear stress τ_{min} for effective mixing with $\tau_{min}=K.\gamma_{min}{}^n$ assuming a power law model for the fluid's rheology.

From these results, it is obvious that the location and the number of the impellers all over the height of the vessel will be a key point in the achievement of full mixing of these tanks (see Figure 5).

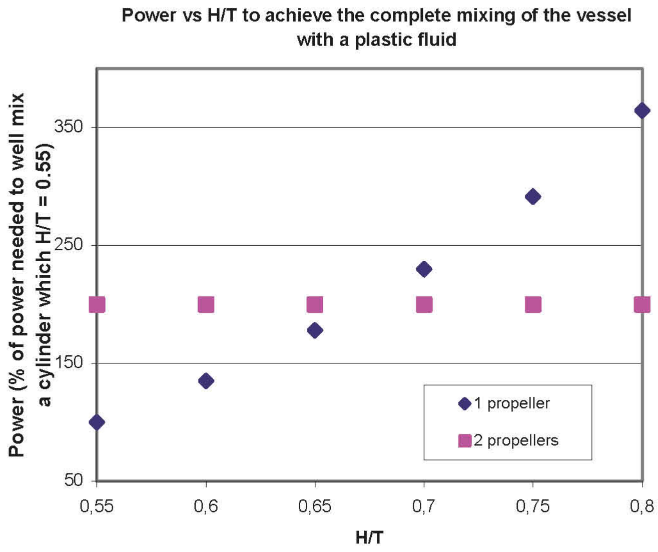

Figure 5

Practical Application

It is clear that accurate data for the rheology are needed to obtain full confidence in the design of the agitator. The viscometer used for this has to cope eventually with slurries having particle top size of few millimeters.

Another way to achieve these measurements is to use an agitator equipped with a precise torque measurement on its shaft and then to plot power vs. rotational speed. With the P_0= f(Re) curve for the impeller used, it is possible to estimate the apparent Reynolds number during the test in slurry and then to calculate the apparent viscosity corresponding to different speed. By knowing the Otto and Metzner constant ks (7) of the impeller (γ = ks.N), it is then possible to have the final curve of μ_a=f(γ).

In Figures 6 and 7 are shown the result of the extrapolation from 50 liters (Figure 6) to 500 m^3 (Figure 7) of a vessel containing 68%w/w Phosphate in water. (industrial agitator power: 110 kW, 2 propellers HPM to ensure good mixing without dead zones in the tank, outlet by pump at the bottom of the tank, liquid height = 9 m, vessel diameter = 8 m). In this case, close cooperation between the agitator designer and manufacturer and the engineering company responsible for the construction of the vessel has led to an optimized configuration minimizing investment as well as operating costs.

For more complex slurries such as thixotropic ones, a pilot test at around a 5m^3 scale using the slurry derived from the industrial process would be preferable to evaluate the build-up ability of this slurry in order to have the maximum confidence in the extrapolation to industrial scale.

Figure 6

Figure 7

Restarting of the agitator after shut-down

When the agitator is stopped (ex : because of a power failure on the grid), solids settle at the bottom of the tank. When the agitator is restarted, depending on how much solids have settled during the stoppage, it will be able to turn .or not.

Tests have been done on alumina precipitators (4500 m^3, 800gpl) to check the variations of the power taken by the mixer just after it has been restarted in settled solids for different durations of stoppages. The current, power, power factor, voltage have been measured every second and the results for two tests are indicated in Figures 8 and 9.

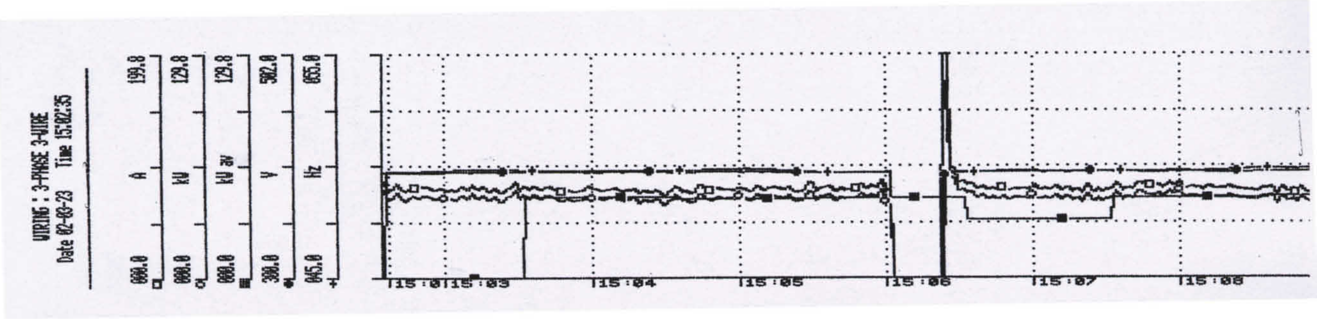

Figure 8 – restart of the agitator after 20 s

Figure 9 – restart of the agitator after 15 minutes

Several tests have been done with many durations of stoppages (20s, 1 min, 3min, 7 min, 10 min, 15 min). From Figure 9, it can be seen that there is a noticeable increase of the power taken by the agitator during about 30 seconds after the restarting.

In fact, after such a duration, the viscosity of the media around the lowest propeller have increased along with stoppage time changing the flow regime from turbulent during normal running into transitional flow. The increase of power during this period is directly linked to the increase of the Power number P_0 along with Reynolds number.

Theoretically, whatever the case studied, this increase of power can be calculated by knowing the characteristics of the viscosity of the settled slurry. Practically, chemical reactions, thixotropy or other detrimental parameters depending on process conditions occurring before and during the stoppage increase considerably the uncertainty of such a calculation.

Application to PECHINEY's high density predesilication process

This method has been applied successfully to this process after several steps.
Two scales have been studied before final industrial scale:

- 1* 45m^3 vessel (dia 4 m, liquid height 3.6m)
- 2* 230 m^3 vessel (dia 6.1 m, Liquid height 8 m)

These vessels have been connected directly to the industrial line in order to be confident in case of extrapolation to larger scales, taking into account operational troubles that could occur during the industrial process.

Basis for design

During the design phases of these two pilot vessels, low viscosities of the slurry have been taken into account.
The Zwietering's correlation has been used to determine the Njs speed.
Three propellers have been installed per tank in order to cope with an eventual increase of viscosity and to reach the homogeneity required by the process to guarantee the same residence time for the smallest as well as the largest solid particles.
Outlet of the slurry was done by pump near the bottom.
Two propeller configurations have been studied during the trial campaign :

- large propellers at slow speed / small width of the blades / (Dm/T) = 0.65 / HPM S Robin Industries
- propellers at larger speed / medium width of the blades/ (Dm/T) = 0.46 / HPM "Baux" Robin Industries

Results

A week after the beginning of the campaign, the tank equipped with the HPM S experienced problems with solids build-up near the bottom as well as power increase. Moreover, the visual observation of the liquid surface highlighted far greater velocities near the center of the vessel compared to those near the walls, which is typical of a pseudosplastic media.

The other agitator configurations equipped with HPM "Baux" were working perfectly well at the same time in the same process conditions. In fact, the shear rate of the HPM "Baux" was found to be far more important than the one of HPM S configuration.

Consequently, after having tested different rotational speeds, a minimum shear rate ($\gamma_{\mu\iota\nu}$) to obtain a well mixed slurry have been defined for HPM Baux and used as one of the criteria for extrapolation.

Applications

More than 30 predesilication tanks with operating volumes up to 1000 m^3 have been designed by Robin Industries for the PECHINEY's process with low specific power.

Accurate rheology data for the slurry are the key point for a successful design with trouble-free running.

Notation

Njs	Just off-bottom solids suspension speed	rpm
γ	Shear rate	s^{+1}
τ	Shear stress	Pa
τ_y	Yield stress	Pa
μ	Viscosity	Pa.s
n	Flow behaviour index	-
K	Consistency index	Pa.s^n
S_{45PBT4}	S coefficient for Pitched 4 blades 45°	
D_m	Impeller diameter	m
C	Impeller clearance from bottom	m
H	Liquid height in the vessel	m
T	Diameter of the vessel	m
Re	Reynolds Number	-

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