Basics in non-Newtonian Mixing for Handling of Tailings and Other High Concentration Slurries

Detlef Klatt[1] and Janin Klatt-Eberle[2]
1. Managing Director
2. General Manager
STC-Engineering GmbH, Waldenburg, Germany
Corresponding author: j.klatt-eberle@stc-engineering.de

Abstract

A precise knowledge of the rheological behavior of highly loaded slurries is essential to design mixing equipment for such applications. Laboratory research with transparent test fluids showing the same flow behavior as the original slurry, the application of analytically-derived models and system cross checking by means of CFD, allows reliable design of large scale mixing equipment. A comparison of these different methods will be shown, followed up by a scale-up to an industrial installation.

Keywords: Non-Newtonian slurry; rheology; mixing; cavity formation; CFD; scale-up.

1. Slurry data

To design efficient and reliable mixing equipment, it is essential to have a close look at the physical properties of the liquid to be mixed. In a first step it is necessary to clarify the basics of properties and definitions to establish a common understanding.

Dispersions

A system in which particles are dispersed in a continuous phase:

- Molecular dispersion $d_P \leq 1$ nm
- Colloidal dispersion $d_P > 1$ nm < 1µm
- Coarse dispersion $d_P > 1$ µm

Suspensions

A system as coarse disperse Dispersion:

- Fine suspension $d_P > 1$ µm ≤ 100 µm → Red mud
- Coarse suspension $d_P > 100$ µm $\leq 1\,000$ µm → Desilication slurry

Figure 1. General definition of slurries.

The above definitions are trivial, however necessary to clarify what shall be further outlined in detail. Considering the particle composition of the two fluids, we can verify that we are dealing with a fine suspension in the case of red mud (dp80 < 100 µm), while the desilication slurry (dp80 > 100 < 900 µm) is surely categorized as coarse suspension. All slurries are in general polydisperse, with a broad particle distribution.

The detailed composition of the respective media to be examined is listed in Fig. 2.
This data shall constitute the basis of the following considerations, knowing well that there are wide deviations in the one direction or another.

			Bauxite slurry	Red Mud
Solids density	ρ_S	[kg/m³]	2 800	3 000
Continuous phase density	ρ_L	[kg/m³]	1 250	1 000
Slurry density	ρ_{SL}	[kg/m³]	1 800	1 600
Solids mass concentration	C_G	[%]	55	57
Solids volume concentration	C_V	[%]	35	30
Solid mass	C_{ms}	[g/l]	990	900
Particle size 80 % passing	d_P	[µm]	800	70

Figure 2. Physical composition of slurries considered.

2. General slurry rheology parameters

The main influencing parameters can be summarized as in Figures 3 to 5.

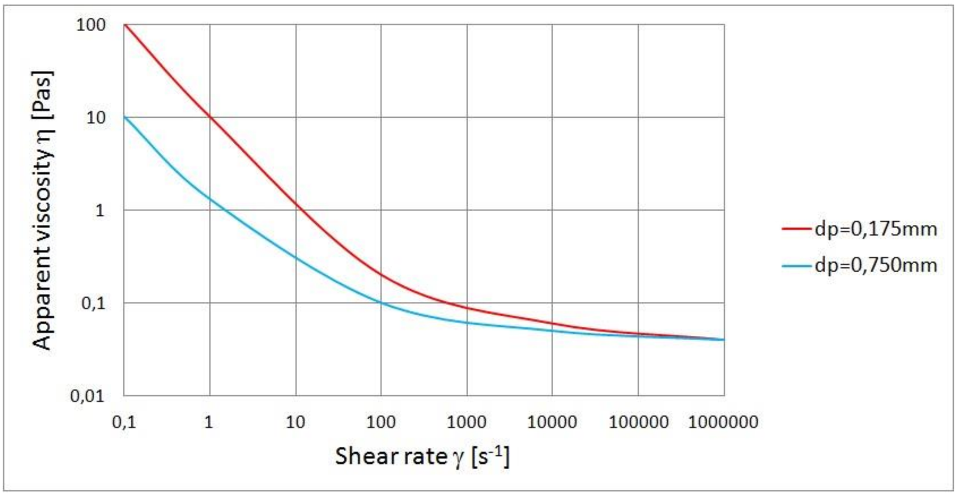


Figure 3. The impact of particle size on viscosity. [1]

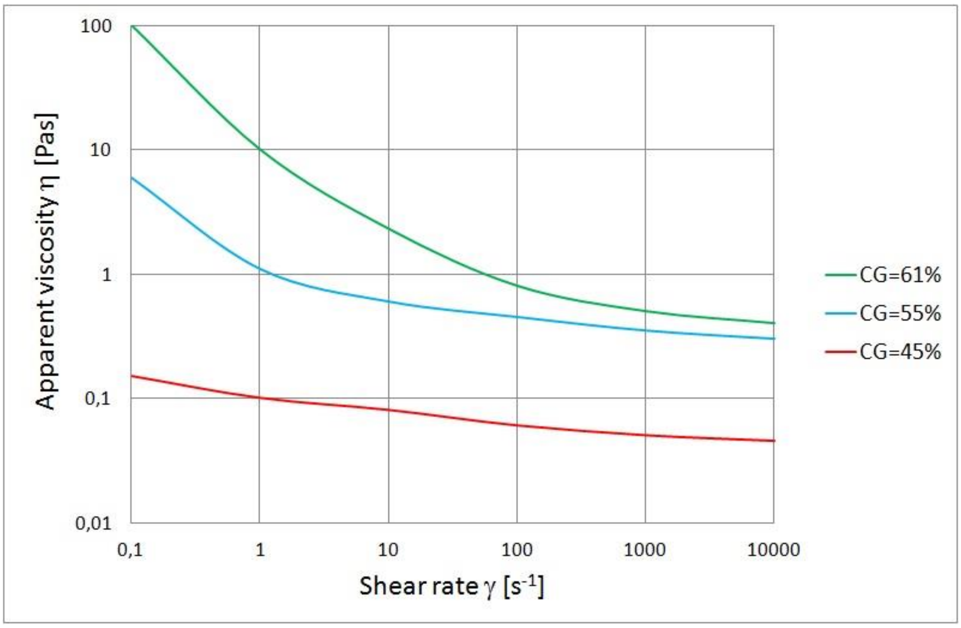


Figure 4. The impact of solids concentration on viscosity. [1]

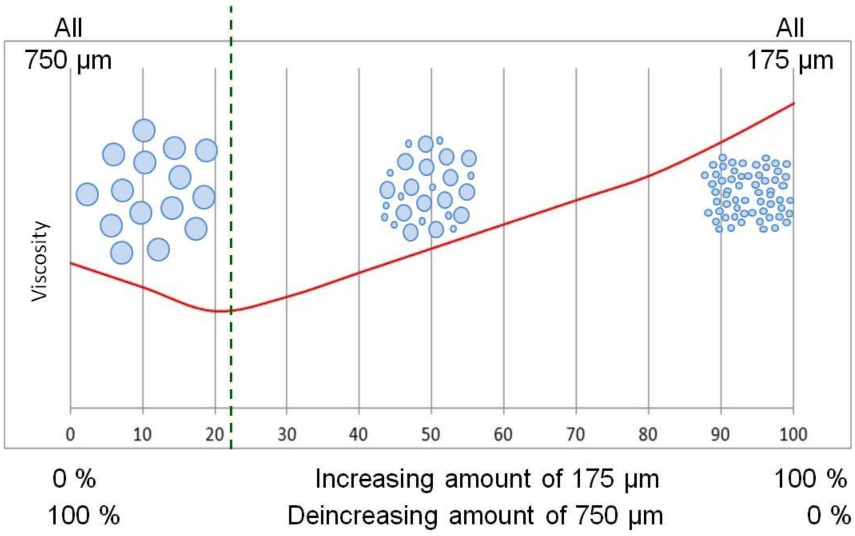


Figure 5. The impact of poly dispersity on viscosity. [1]

Parameters influencing the rheological behavior of slurries are;

1. Solids concentration
2. Granulometry
3. Viscosity of continuous phase
4. Temperature

For all suspensions in question, it has been demonstrated by numerous publications that finer material has higher slurry viscosity than the coarser material. This difference disappears at very high shear rates. As most slurries we have to deal with are polydisperse, usually with a broad spectrum of grain size, this principle prevails. However, polydispersity changes viscosity in between the borders. A further influencing factor is the solids concentration, one of the important viscosity determining factors. As we usually have low viscosity media as the continuous phase, this influence is negligible. Temperature also need not be considered.

3. Specific rheology parameters for the slurries in question

For the slurries considered, the viscosity data as per Figure 6 were measured and are in good accordance with literature. Also here it is obvious, that the coarser material (Bauxite slurry) has the lower viscosity. All in all however, the slurries show non-newtonian flow behavior, particularly shear thinning, and consequently the existence of a yield stress can be assumed.

Figure 7 shows the yield stresses related to solids concentration of red mud slurries.
It is obvious, that depending on the red mud source, (sample 1 to 3) there are remarkable differences in flow behavior. The yield stress, at a solids concentration of about 57%, as used in the sample case later, lies between τ_y = 60 to more than 300 Pa, for the worst case. The apparent viscosity versus shear rate as per Fig. 4 did not show equivalent fluctuations et al.

Figure 8, the yield stress for Bauxite slurry shows, also based on granulometry, considerable differences in the magnitude of the yield stress, however at a far lower stress level. It is interesting that the differences narrow with increasing grain size. At a solids mass concentration of C_G = 55 %, as used for the desilicator sample calculation, a yield stress of τ_y = 2.5 Pa would be applicable.

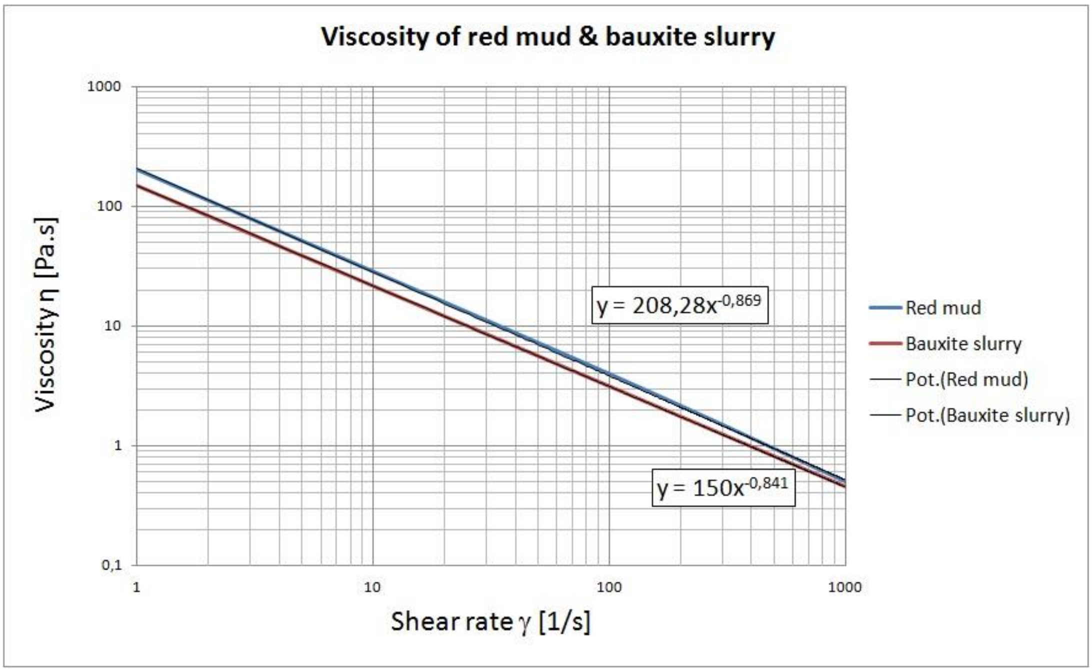


Figure 6. Apparent viscosity of red mud & bauxite slurry. [2]

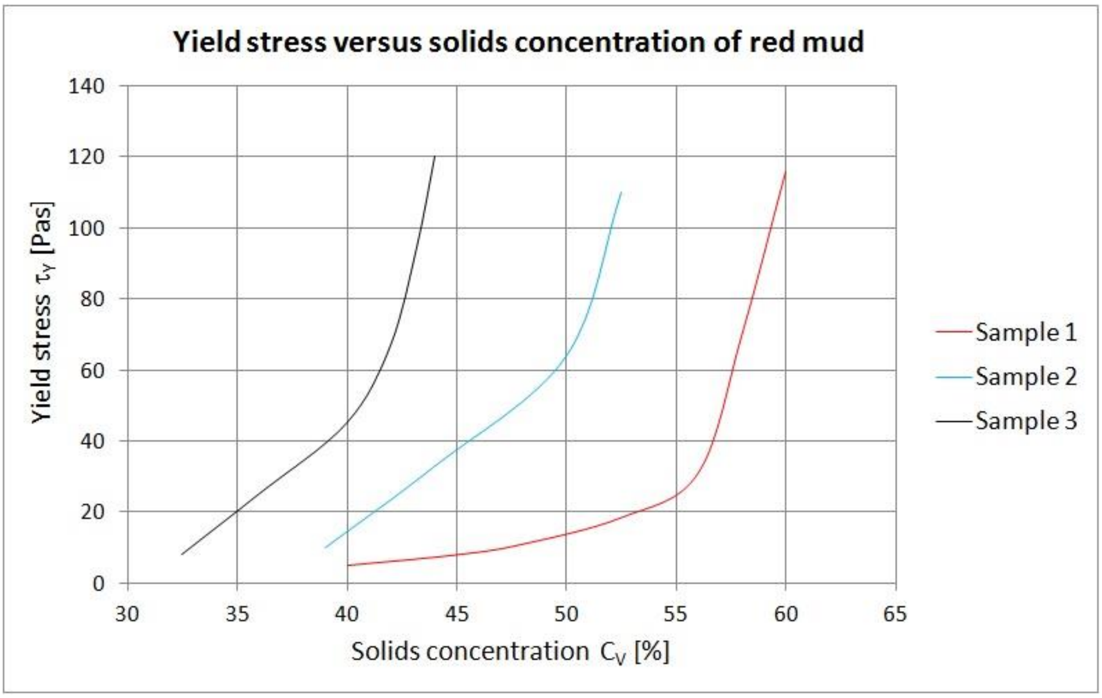


Figure 7. Yield stress versus solids concentration of red mud. [3]

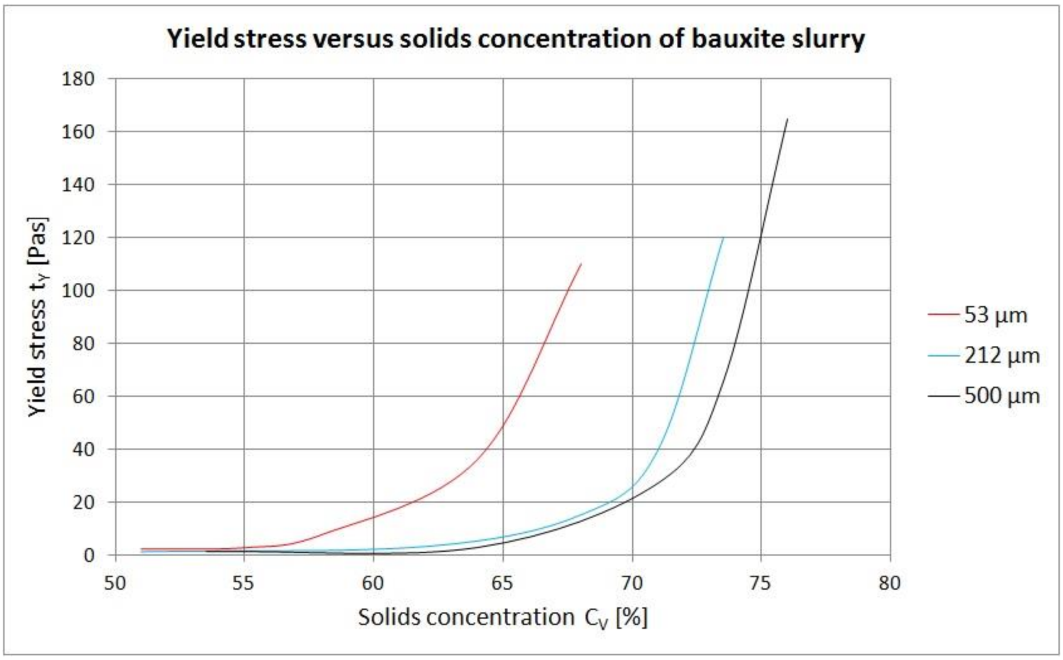


Figure 8. Yield stress versus solids concentration of bauxite slurry. [4]

4. Mixing considerations

The photographs in Figures 9 to 11 show very clearly that mixing of yield stress fluids requires careful consideration of the flow behavior of those liquids.
While according to Figure 9, for a liquid with τ_y = 12 Pa, the mixed cavern reaches the wall. Figure 10, with τ_y = 33 Pa teaches us that speed or impeller diameter are not sufficient any longer to create a wall reaching cavern. The later one even makes clear that overall mixing within the cavern cannot be well achieved, demonstrated by the color separation between top and bottom of the cavern. Figure 11 with a dual stage system demonstrates perfectly that it is possible to create 2 independent cavities which might be well mixed in themselves, but have no connection to each other, and a sensible overall blending is simply impossible at the lowest speed. This already shows clearly that the solution for a sensible mixing requires more thought than indicated by the classic mixing cases with Newtonian liquids.

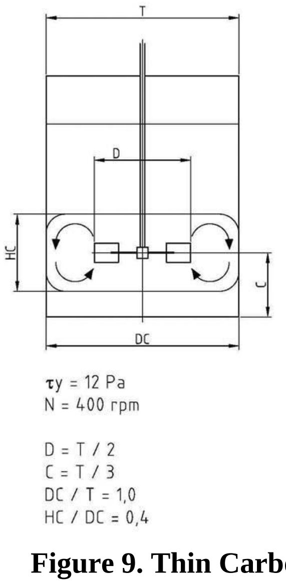


Figure 9. Thin Carbopol solution yield stress 12 Pa at 400rpm. [5]

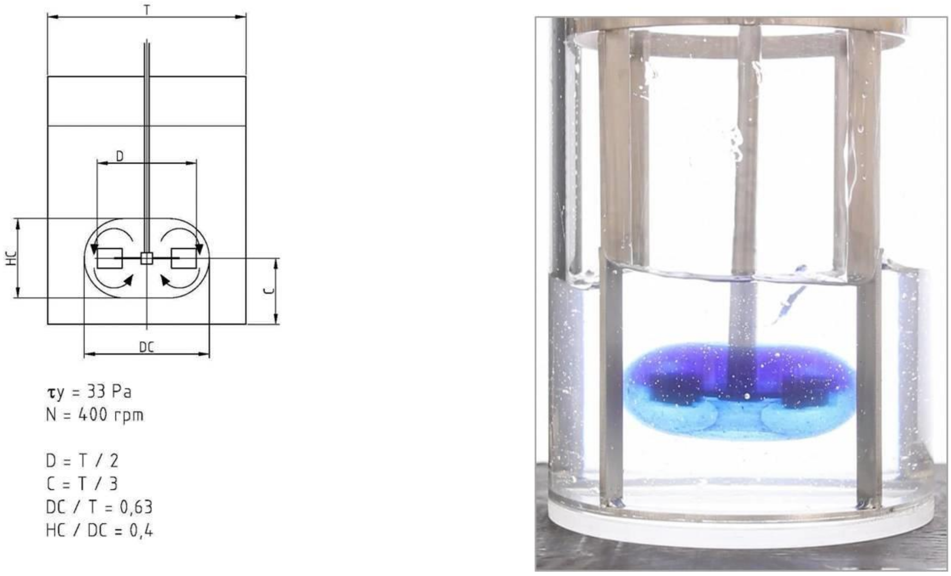


Figure 10. Thick Carbopol solution yield stress 33 Pa at 400rpm. [5]

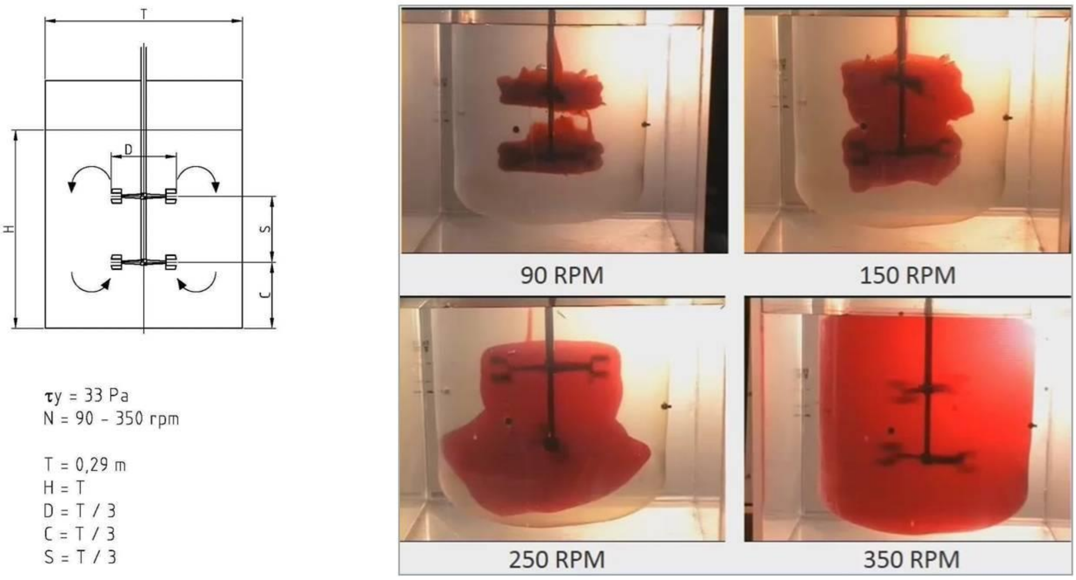
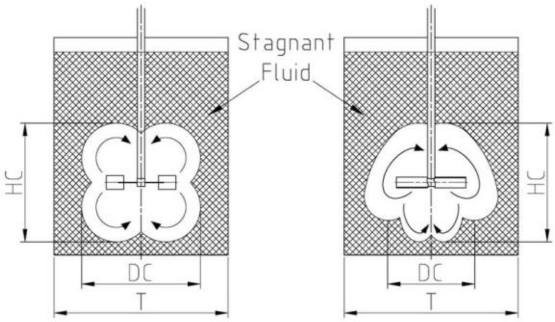


Figure 11. Thick Carbopol solution yield stress 33Pa. [5]

The summary in Figure 12 below of available literature on the subject of cavern size calculation for impellers operated in yield stress fluids, allows a quite reliable prediction of the requirements. The theoretical approach for a known mixing solution can be handled according to the equations illustrated.

Some important details should be considered, to use those equations properly;

- The yield stress τ_y is the most important factor and has to be determined carefully.
- The power number P_O has to be taken from the impeller specific Power number versus Reynolds curve applicable for the chosen impeller, or as calculated above, with a curve fitting equation. To calculate the power number, one has to consider the Reynolds number derived by calculating with the apparent viscosity from the viscosity versus shear rate function. The principle way will be shown in the following examples.



Metzner-Otto Constants, K

$$K = \frac{\dot{\gamma}}{N}$$

Impeller type	Constant, K
Propeller	10
Rushton turbine	12
Flat-blade turbine	12
Pitch-blade turbine	12
Anchor	25
Helical ribbon	30

Cavern size $\left(\frac{D_C}{T}\right)^3 = \frac{1.36}{\pi^2}\frac{P_O * \rho N^2 T^2}{\tau_y}$

P_O = Power number at the operation point for a single stage

For the Counterflow impeller

$$P_O = \frac{29}{Re} + \frac{1}{Re^{1,5}} + \frac{2,2}{Re^{1,8}} + 0,25\ [-]$$

$$Re = \frac{N * D^2 * \rho}{\eta}\ [-]$$

$$\dot{\gamma} = K_{M/O} * N \left[\frac{1}{s}\right]$$

$$\eta = C * \dot{\gamma}^n\ [Pas]\ 32{,}7\ Pas\ for\ red\ mud$$

Variables an units

P_O	Power number	[-]
T	Vessel Ø	[m]
D_C	Cavern Ø	[m]
D	Impeller Ø	[m]
H_C	0,4xD_C Cavern height	
N	Shaft speed	[rpm]
τ_y	Yield stress	[Pa]
γ	Impeller shear rate	[1/s]
Re	Reynolds number	[-]
η	Apparent viscosity	[Pas]
n	Flow index	[-]
ρ	Density	[kg/m³]
C	Consistency factor	[--]

Figure 12. Shape and calculation of caverns in a shear-thinning suspension.[6]

5. Examples of mixer design

In the case of Red Mud Liquefaction (see Figure 13), a single stage arrangement is chosen, as complete mixing throughout the vessel is not required. The impeller creates a cavern in which an apparent viscosity of η_a = 32,7 Pas is established due to the impeller produced shear rate. The liquefied material is pumped back partly above the impeller and helps to pre dilute the stream coming from the filters. The mixed material out of the impeller created cavern is transferred by a booster pump to the high-pressure pump, transporting the material to deposition. The calculated impeller power for this case is 34 kW, indicating a 45 kW drive motor must be installed.

The desilicator example (Figure 14), where overall mixing is required, must be approached differently. Good contact between solids and caustic liquor must be achieved to react and precipitate the silica. This reaction is best achieved at very high solids concentration, which on the other hand creates a highly viscous media, defining the mixing requirements. Solids suspension as mixing task is not a significant consideration, as the solids settling tendency is practically nil at this viscosity level.

Dispersion to homogenize and create a reaction interface has to be considered, meaning a complete overall mixing with as few stagnant zones as possible has to be achieved. This makes a multi-stage system inevitable, where the caverns must be overlapping to achieve overall material transport throughout the vessel. The apparent viscosity here is η_a = 128 Pas because of the low impeller shear rate at N = 6 rpm. The impeller power requirement (P) is 35 kW, and here also a 45 kW motor would be sufficient.

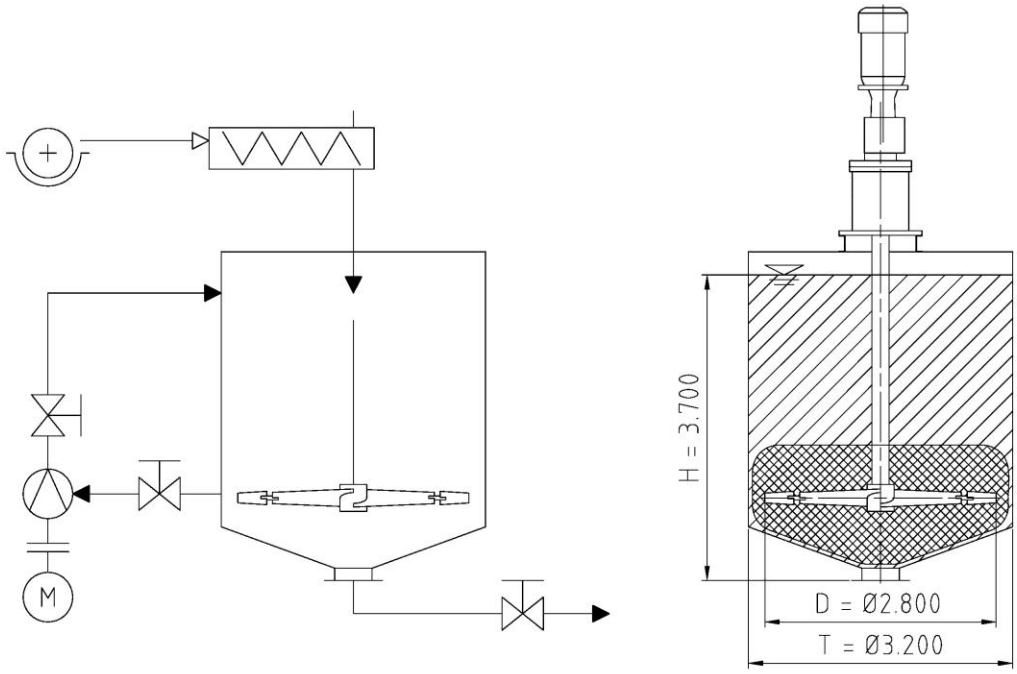


Figure 13. Red mud liquefaction.

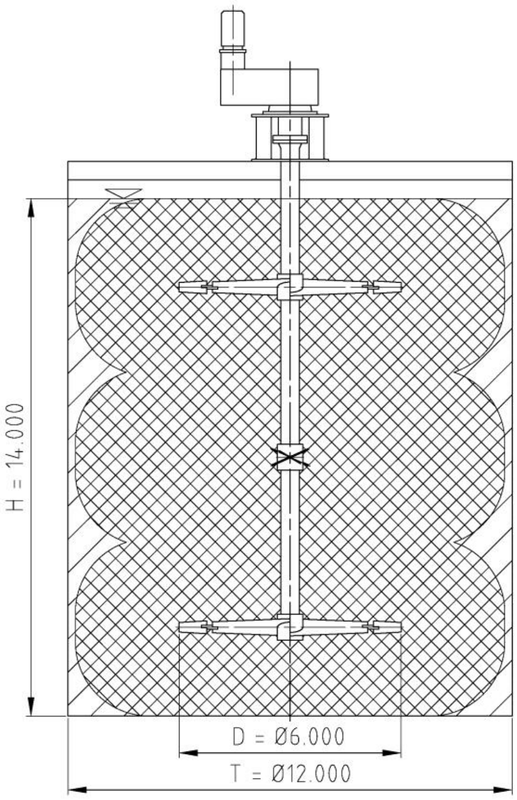


Figure 14. Desilicator.

6. Conclusions

- Reliable mixer design requires
  1. Precise definition of the mixing requirements
     1.1. Specifying mixing task and quality of mixture
  2. Exact verification of slurry data
     2.1. Composition and flow behavior
  3. Use of available design tools and data
     3.1. State of the art analytical calculation methods
     Use of CFD Tools for flow
     Use of FEM Tools for mechanics
  4. Employing lab tests for problem visualization
     4.1 Flow visualization in transparent media
     Verification of physical data of the slurry
     Determination of mixing parameters as mixing time and mixing quality

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