Sludge Suspension in Waste Storage Tanks

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There are various types of solids which require suspension in tanks in the chemical processing industry. For discrete particle systems in impeller-agitated tanks, the concept of minimum impeller rotational speed has been developed and extensively studied. The main process objective is off-bottom suspension for mass transfer in particle dissolution or growth studies. Homogeneous suspensions are not necessarily obtained or desired.

Other processes also exist in the general area of solid suspension that are far less studied. One is sludge suspension where particles are fairly small (e.g., 10 μm), but once suspended, form uniform suspensions easily. The suspension process becomes one of eroding the sludge layers. In many cases, the sludge can be considered to be a paste or a high-viscosity liquid.

In large storage tanks, jets rather than impellers are used for mixing and solid suspension. Jets often are formed by submerged rotating pumps, commonly referred to as slurry pumps. In sludge suspension applications, the jets from the slurry pumps form circular sludge-free cavities. The radius of these circular cavities, called the cleaning radius, is used often as a measure of the suspension capability of slurry pumps to suspend solid sludges.

Although there is considerable technical literature on mixing and solid suspension in impeller-agitated tanks, studies on jet-induced suspension of a paste or sludge in large storage tanks using slurry pumps are unavailable in the open published literature.

The objective of this paper is to determine how the cleaning radius and suspension rate change with time for a typical sludge material and to provide a phenomenological model which explains the results in a general fashion.

Background

The concept of a cleaning radius for a slurry pump can be established from an integral momentum balance where a strong jet is assumed to strike the sludge. The force of the jet striking the sludge surface is modeled as:

$$F_j = \rho V_x^2 A / 2g_2 \tag{1}$$

where

F_j = force of the jet
ρ = density
V_x = velocity of the jet at the point where the jet strikes the sludge
g_2 = gravitation constant
A = area of impact

The resisting force is due to a general stress, τ, arising from the sludge. Assuming V_x is proportional to $U_o D_j / X$, the cleaning radius can be obtained from:

$$X(\tau)^{1/2} = K(\rho)^{1/2} D_j U_o \tag{2}$$

if τ is known. The cleaning radius is usually given as a static quantity, not a time-dependent quantity, in the description of slurry pumps.

Cleaning radius equations pose difficulty, generally because such equations contain no information about how long it will take to obtain a particular cleaning radius. Since this is obviously an important question, we can seriously question the actual utility of cleaning radius equations based upon an integral momentum balance.

Experimental Equipment and Procedure

The slurry pump used in this study was a Bingham-Willamette long-shaft centrifugal pump with suction in the bottom center of the volute. The discharge ports were two 38.1-mm (1.5-in.)-dia. nozzles, 180° apart on the sides of the pump volute. Jets mix by entrainment and have much larger diameters than their nozzle diameter in relatively short distances. The pump was equipped with 111.8-kW (150-hp) motor and was mounted on a turntable which rotated at 0.00333 s^{-1} to 0.00555 s^{-1} (⅕ to ⅓ rpm). According to specifications given by the manufacturer, the pump delivered 0.00757 m^3/s (1,200 gpm) with the pump impeller rotating at 30 s^{-1} (1800 rpm). The waste storage tank, Tank 16 at the Savannah River Plant used in this study, was

25.9 m (85 ft) in diameter and 8.23 m (27 ft) in height, and contained settled sludge which could vary from 0 to 3 m (10 ft) in height. The sludge height in this study was 0.378 m (1.24 ft). The experimental procedure consisted of slurrying the sludge, draining the tank, and then noting the cleaning radius. The sludge was suspended in an aqueous supernate layer.

The weight fraction of solids in the sludge was 20 to 30 wt. %, and the specific gravity of the sludge was 1.2 to 1.4. The settling rates of slurry varied inversely with wt. % solids and have been reported to be on the order of 4×10^{-2} mm/s (5 in/h) at 1.5 wt. % to 7×10^{-4} mm/s (0.1 in./h) at 13 wt. %. The size of sludge particles was 5 to 10 μm. The typical composition of the sludge was available but was considered unimportant for this study.

The typical rheological data for the sludge are shown in Figure 1. The shear stress levels were very high above a certain shear rate (e.g., 150 s^{-1}), and ranged between 1 and 33 Pa. At low shear rates, the shear stress decreased rapidly to zero as shear rate decreased to zero. In a rough fashion, the material behaved as if it had two viscosities: a low viscosity at high shear rates (100 s^{-1}) and a very high viscosity at low shear rates. At very low shear rates (e.g., 10 s^{-1}), the material can be considered a paste or a very viscous liquid.

The average fluid shear rates in tanks agitated by rotating impellers are roughly around 10 times the impeller rotational speed. Using this as a basis, the average shear rates occurring in a waste tank agitated by a jet from a slurry pump should be below 300 s^{-1}. As a result, the shear rates experienced by the sludge away from the slurry pumps should reach very low values (e.g., 1.0 s^{-1}). Wichterle et al. (1988) provided shear rate data on vessel walls that agree with this conclusion.

Experimental Results

Typical time and position data for the sludge interface in Tank 16 are shown in Figure 2 and were fitted to the following equation:

$$X = 1.25(t)^{0.36} \tag{3}$$

or

$$t = (X/1.25)^{2.78} \tag{4}$$

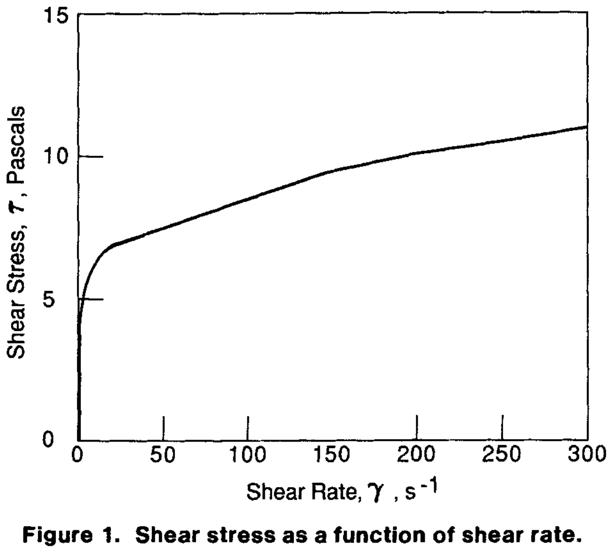

Figure 1. Shear stress as a function of shear rate.

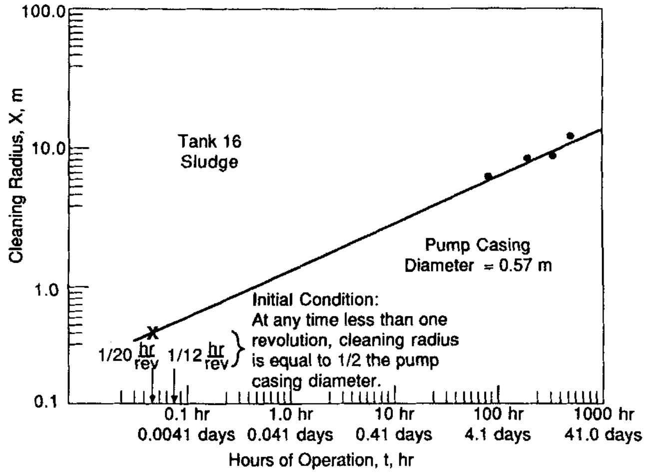

Figure 2. Cleaning radius as a function of time.

where X is the cleaning radius in m, and t is time in hours. The regression coefficient for this equation is 0.986. Eqs. 3 and 4, and the data in Figure 2 show, there is no leveling-off of the cleaning radius to a fixed value at large times. It is also obvious that large times are required to obtain large cleaning radii. For example, for the cleaning radius to move from 10 m to 10.5 m, two days are required. Differentiation of Eq. 3 shows that the slurry/sludge interface decelerates very slowly with time.

Processing experience for different sludges indicates that the cleaning radius/time relationship is not dependent upon the rheology of the different sludges. Rheological characteristics of sludges have not been included in the cleaning radius/time relationship.

The suspension rate of the sludge can be defined as the area of sludge suspended per time, or $d(X^2)/dt$, since X is the cleaning radius. In terms of the equation given above, the suspension rate varies with time following the relationship:

$$d(X^2)/dt = 1.125t^{-0.28} \tag{5}$$

As can be observed by this equation, the suspension rate is a weak function of time and can be considered fairly constant over short periods of time (e.g., one day). The suspension rate at 200 h was about 0.227 of that occurring at 1 h; the suspension rate at 500 h was 0.176 of that at 1 h.

Phenomenological Model for Sludge Suspension

The sludge interface moves in an orderly manner which indicates that an analytical solution may be possible and that a model for the cleaning radius/time relationship can be developed phenomenologically from the physics of the sludge suspension process. First, the jet from the slurry pump does not strike the sludge bank directly for any extended period of time. Instead, the jet flows up and over the sludge bank as shown in Figure 3. By doing so, a recirculation zone is established at the slurry/sludge interface. If the pump is totally submerged in the sludge, the pump and jets quickly emerge from the sludge and sludge banks will be formed. At the slurry/sludge interface, the no slip condition holds: i.e., the flow velocity at the surface of the sludge is the same as the sludge surface.

The demise of the sludge interface is due to an erosion dilu-

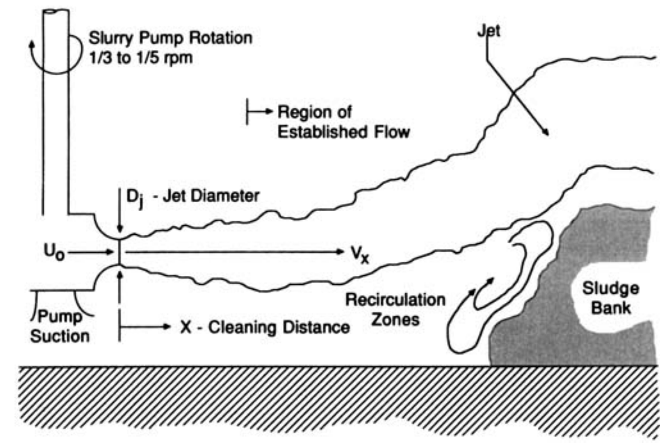

Figure 3. Sludge suspension process.

tion process. The slurry liquid can be envisioned as penetrating into a layer of freshly exposed sludge. This dilution effect weakens the sludge, permitting the erosion of sludge particles from the interface. The particles are removed from the vicinity of the sludge interface by the periodic passing of the entrained jet flow over the interface and circulation flow induced by the jet.

The transport of the sludge away from the interface has to obey continuity. If the jet and entrained sludge flow are assumed to be a constant density cylindrical flow with only a radial velocity component, the equation of continuity becomes:

$$\partial(rV_r)/\partial r = 0 \tag{6}$$

Integrating:

$$V_r = C_1/r \tag{7}$$

where C_1 is some fraction of U_oR_c. The transport of the sludge away from the interface is proportional to the discharge velocity of the slurry pump and to the velocity of the interface. The last proportionality can be written as:

$$(V_r)_{\text{interface}} = K_1(V_r)_{\text{fluid}} \tag{8}$$

The presence of the sludge bank causes the radial flow to decelerate, forming the eroding recirculation zone in front of the sludge bank as shown in Figure 3. The deceleration of the radial jet can be written as $V_r\partial V_r/\partial r$, which represents the deceleration in the scrubbing force of the radial jet on the slurry/sludge interface. The phenomenological model assumes that there is a direct proportionality between the deceleration of the radial jet and the deceleration of the interface or

$$(dV_r/dt)_{\text{interface}} = K_2(V_r\partial V_r/\partial r)_{\text{fluid}} \tag{9}$$

Substituting Eq. 8 into Eq. 9 and assuming that K_2 is approximately K_1^2 based upon momentum rate/force scaling, the equation for the interface can be written as:

$$(dV_r/dt) = (V_r\partial V_r/\partial r) \tag{10}$$

where V_r on both sides of the equal sign is the velocity of the interface of the sludge. The sludge is not moving, but the eroding sludge/slurry interface has the kinematic behavior of a very viscous fluid.

Integrating Eq. 10, the relationship between cleaning radius and time can be obtained as:

$$t = X^2/(2C_1) + C_2 \tag{11}$$

where C_1 and C_2 are constants. C_1 is the same C_1 constant in Eq. 7. If the cleaning radius is zero at time equal to zero, then C_2 can be assumed to be zero or

$$t = X^2/(2C_1) \tag{12}$$

If the cleaning radius has a fixed value, X_o, at time equal to t_o, then the equation becomes:

$$t = (X^2 - X_o^2)/(2C_1) + t_o \tag{13}$$

The jet, the induced circulation flow, and sludge bank are not necessarily cylindrical. If spherical expanding jet and sludge bank were assumed and spherical coordinates are used in the same manner, the cleaning radius/time relationship would appear as:

$$t = X^3/(3C_1) \tag{14}$$

where C_1 is the same C_1 constant, and the constant of integration is assumed to be zero.

It should be noted that the exponents of the cleaning radius in the above equations bracket the exponent 2.78 which was obtained experimentally. Actually, the jet and sludge bank are neither cylindrical nor spherical in nature.

It should be noted that if the slurry pump jets were made more cylindrical in nature, the experimental exponent would likely approach a value of 2, which is advantageous for reducing the time necessary for sludge suspension. The model also suggests that the outside casing diameter of the pumps should be made as large as possible. This changes the initial time condition which will reduce cleaning times substantially. Pump effectiveness in sludge suspension in the present geometries is limited to:

$$X \,\alpha\, t^b \tag{15}$$

where b varies between 0.33 to 0.5.

In the above relationship between cleaning radius and time, no rheological properties of sludge are needed to predict the cleaning radius. Once suspended, the slurry has a very low settling rate and can be easily maintained at low agitation levels.

There is a point where a jet in an enclosed tank becomes overwhelmed by the jet entrainment flow and disappears into the recirculation flow of the tank. This disappearance length for jets in sludge suspension may limit the cleaning radius. There may also be a X/T effect, which influences the jet behavior and limits the cleaning radius as well.

Notation

A = area of contact
b = time exponent
C_i = various constants

D_j = jet diameter at nozzle, nozzle diameter
F_j = jet force
g_c = gravitation constant
K = constant
K_1, K_2 = scaling constants
R_c = casing or volute radius of pump
r = radial direction or radial position
T = tank diameter
t = time
t_o = a fixed time
U_o = average jet nozzle velocity
V_x = velocity in the x direction or horizontal direction
V_r = velocity in the radial direction
X = cleaning radius or distance of jet travel
X_o = cleaning radius at a fixed time t_o

Greek letters

ρ = fluid or slurry density
τ = shear stress
γ = shear rate

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