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Optimum solids concentration for solids suspension and solid–liquid mass transfer in agitated vessels

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ABSTRACT

The effect of solids concentration on specific impeller power consumption and solid–liquid mass transfer coefficient was investigated in a 0.2 m diameter baffled agitated vessel with standard six-bladed Rushton turbine for solids concentration up to 0.40 (v/v). It was found that the increase of solids concentration significantly increases the mass transfer coefficient up to an optimum solids concentration and decreases thereafter when the system is operated at a just-suspended condition. The increase in mass transfer coefficient with an increase of solid concentrations is mainly due to the increase in N_{js} (critical impeller speed) with increasing solids concentration, thereby leading to an upsurge of turbulence around the particles. The solids concentration at which the highest mass transfer coefficient is obtained is designated as the effective solids concentration. In a geometrically similar 0.3 m diameter tank, the trends in impeller energy efficiency and solid–liquid mass transfer coefficient values with increasing solids concentration are similar. The experimental data are satisfactorily correlated using the concept of the Kolmogoroff's theory of isotropic turbulence to develop an equation to estimate the solid–liquid mass transfer coefficient in agitated vessels.

1. Introduction

Mechanically agitated vessels are employed in mineral processing and chemical industries to achieve solids suspension for reactions, leaching, digestion, precipitation and adsorption. The mass transfer between solid and liquid phases is essential for such operations. There is continual pressure for the industries to increase the production rate in existing processes. One method of achieving an increased production rate is to increase the solids concentration in the operations mentioned above. Operating at high solids concentrations to achieve process intensification for increased production throughput is an attractive option (Wu et al., 2010). However, an increased solids concentration will subsequently influence various operating parameters such as the impeller speed and power required to achieve solids suspension and solid–liquid mass transfer.

There have been many studies in the literature on solid–liquid mass transfer in agitated vessels but a majority of them involve low concentration slurries. The investigation of mass transfer in high solids concentration slurries is not well covered in the literature. The main reason for this gap is

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Nomenclature

$(C_{Na})_0$	initial NaOH concentration (mol/m^3)
$(C_v)_{eff}$	effective solids concentration (v/v)
$(C_v)_{op}$	optimum solids concentration (v/v)
A	constant in Eq. (10)
a_p	particle interfacial area per unit volume (m^{-1})
B	baffle width (m)
C	impeller to tank bottom clearance (m)
C_L	concentration in the bulk of liquid (mol/m^3)
C_{Na}	NaOH concentration (mol/m^3)
C_s	concentration at the solid surface (mol/m^3)
C_v	solids concentration (v/v)
D	impeller diameter (m)
d_{32}	Sauter-mean solid diameter (m)
D_A	diffusion coefficient (m^2/s)
d_p	solid particle diameter (m)
g	gravitational acceleration constant (m/s^2)
H	liquid height (m)
k	constant in Eq. (16)
k_{SL}	solid–liquid mass transfer coefficient (m/s)
$k_{SL}a_p$	solid–liquid volumetric mass transfer coefficient (1/s)
M	rate of diffusional mass transfer (mol/m^3 s)
M_L	mass of liquid (kg)
M_s	mass of solids (kg)
N	impeller rotational speed (rps)
N_{js}	impeller speed at just off-bottom suspended condition (rps)
N_p	impeller power number ($P/\rho_L N^3 D^5$)
P	impeller power consumption (W)
P_{js}	impeller power consumption at N_{js} (W)
Re	Reynolds number
S	constant in Zwietering's Eq. (17)
Sc	Schmidt number
Sh	Sherwood number
T	tank diameter (m)
t	time (s)
X	ratio of mass of solids to mass of liquid (kg solid/kg liquid)

Subscripts

js	just off-bottom suspended condition
L	liquid
s	solids
SL	solid–liquid

Greek symbols

α	exponent in Eq. (17)
ε	energy dissipation rate (W/kg)
ε_{js}	impeller specific power at just off-bottom suspended condition (W/kg)
μ_L	liquid viscosity (Pa s or kg/m s)
ρ_L	liquid density (kg/m^3)
ρ_s	solid density (kg/m^3)
ρ_{slurry}	slurry density (kg/m^3)
τ_a	absolute torque (N m)
τ_m	measured torque (N m)
τ_r	residual torque (N m)
η_r	viscosity of the continuous phase (Pa s)
η_{slurry}	apparent slurry viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
ϕ_m	maximum solids volume fraction

the perceived difficulties involved in carrying out experimental work with high concentration slurries. Numerous studies on solid–liquid mass transfer in agitated vessels have been reported in the literature. Many of them involved solid to liquid mass transfer (dissolution) operations with fairly high inert particle concentrations, but low active particle concentrations. Among the few studies reported on liquid to solid mass transfer (adsorption) operations, most of them are often restricted to systems with solids concentration less than 0.01 (v/v) where the interaction between the particles is negligibly small (Kato et al., 1998; Pangarkar et al., 2002; Kasat and Pandit, 2005; Tagawa et al., 2011). Harriott (1962) reported no effect of solids concentration on the mass transfer coefficient for solids concentrations between 0.001 and 0.053 (v/v). Lal et al. (1988) made a similar observation, but for systems with solids concentrations up to 0.10 (v/v). Conversely, Cline (1978) used a solids concentration range of 0.05–0.40 (v/v) at a constant impeller speed and showed that the mass transfer coefficient decreases with increasing solids concentration. Harriott (1962) developed a correlation relating the solids concentration up to 0.30 (v/v) to mass transfer coefficient. He predicted that the mass transfer coefficient would increase with an increase in solids concentration by assuming that all the particles are surrounded by a spherical volume of fluid. However, he could not successfully validate his predictions with experimental data probably because of the wide range of particle sizes involved in his experiments.

In solid–liquid operations, particles are driven by the turbulent liquid motion and the space between the particles is filled with the suspending fluid. But in solid–liquid mass transfer, the diffusivity of solute either from or to the solid surface is controlled by hydrodynamic interactions around the particles. The hydrodynamic environment depends on the rate of renewal (also known as relative velocity) of the liquid layer near the solid surface. The renewal of the boundary layers varies from point to point within the vessel and depends on the intensity of turbulence around the solid surface and the convective liquid velocity distribution in the vessel (Paul et al., 2004). Hence, it is recommended to operate the impeller at a critical speed to maximise the solid surface area for mass transfer. The rate of diffusion driven mass transfer between solid and liquid phases is mainly affected by turbulence. As the flow becomes more turbulent, the rate of diffusion increases (Sterbacek and Tausk, 1965). Solid–liquid mass transfer is a film diffusion controlled process where the mass transfer rate is highly dependent on the refresh rate of the film around the particles. The higher the film refresh rate, higher the mass transfer rate. The diffusional mass transfer, M, is defined by the following equation:

$$M = k_{SL} a_p (C_s - C_L) \quad (1)$$

where k_{SL} is the solid–liquid mass transfer coefficient, a_p is the interfacial area per unit volume, (C_s–C_L) is the concentration driving force, C_s is the solute concentration at the solid surface and C_L is the solute concentration in the bulk of the liquid. It is clear that the mass transfer rate M can be increased