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Assessing solids concentration homogeneity in Rushton-agitated slurry reactors using electrical resistance tomography (ERT)

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ABSTRACT

Uniform and efficient particulate–liquid contact is of critical importance in solid–liquid systems. Typically, complete homogeneity of the particulate suspension is desired, but not achieved. In mechanically agitated contactors, the critical impeller speed for off-bottom suspension, N_{js}, and cloud height are used to assess solids distribution across the axial axis as an indicator of suspension efficiency. Further, various, but inconsistent, mixing indices have been proposed previously to quantify homogeneity.

In this paper, the definition of mixing indices is extended to describe homogeneity in terms of the average of the standard deviation in solids concentration across the axial and radial directions as well as across the overall reactor. These mixing indices are quantified using data collected using electrical resistance tomography (ERT) in which an unstructured mesh matching the vessel geometry was used during reconstruction.

The average standard deviation of solids concentrations in each volume element across four planes and seven annuli provided the axial (MI_z) and radial (MI_r) mixing indices. Combined data across the 28 regions provided the overall mixing index (MI_o). These indices were compared across three particle size distributions, three solids concentrations and five impeller speeds. The data demonstrate inhomogeneity in solids concentration across both the radial and axial directions as a function of operating conditions. For the coarse and medium particle fractions (600–850 μm and 425–600 μm), MI_o is dominated by MI_z whereas MI_r dominated MI_o for the fine particle fraction (106–212 μm). In all cases, homogeneity of suspension decreases with decreasing solids concentration across the range 5–20% by volume. Homogeneity improves with increasing impeller speed, up to approximately $0.8N_{js}$ for the medium and coarse fractions. Little dependence of mixing index on impeller speed was observed for the fine fraction across the range $0.5N_{js}$ to $1.4N_{js}$. The limited dependence of homogeneity on impeller speeds above $0.8N_{js}$ suggest significant energy savings can be achieved without loss of suspension by operating at impeller speeds below N_{js}.

1. Introduction

The contacting of the liquid phase and particulates is a key requirement of many process engineering applications, involving two-, three-or four-phase systems. These include suspension of particulates for leaching, contacting of microbial phase and solid substrate, contacting of particulates with air bubbles in flotation, formation of aggregates or flocs and contacting of the saturated solution and seed crystals during crystallisation. This is illustrated by the copious literature on mixing in stirred tank reactors, reviewed in texts such as Nienow (1968, 1997), Oldshue (1983), Shamlou and Koutsakos (1989) and Sharma and Shaikh (2003).

Despite the strong influence of contacting, the associated hydrodynamic environments created and their influences on mass transfer, turbulence eddies and shears forces amongst others, the description of solids suspension in such slurry reactors is seldom complete. Most typically, the concept of critical suspension speed, introduced by Zwietering (1958) and extended by Nienow (1968), Armenante and Nagamine (1998) and Van der Westhuizen and Deglon (2008) amongst others, has been applied to ensure off-bottom suspension. The critical suspension speed or "just suspended" condition, N_{js}, is defined as the minimum impeller speed at which all solids are just suspended off the bottom of the tank. Zwietering developed the correlation given in Eq. (1) to relate critical suspension speed to operating parameters in the ungassed system (Van der Westhuizen and Deglon, 2008):

$$N_{js} = S d_p^{0.20} B^{0.13} \nu^{0.10} g^{0.45} \left(\frac{\rho_S - \rho_L}{\rho_L}\right)^{0.45} T^{-0.85} \tag{1}$$

where S is a function of D/T, C/T and impeller type. This, however, does not describe completely the homogeneity of the solids

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distribution in the slurry. Cloud height has been used as an alternative measure of solids suspension, considering distribution through reactor (Bittorf and Kresta, 2003). Zehner and Tebel (1984) defined the critical suspension speed as that at which the cloud height reached 90% of the liquid height.

A variety of methods have been used to investigate solids suspension. These include direct sampling of the reactor (Baldi et al., 1981; Barresi and Baldi, 1987), optical attenuation, laser Doppler velocimetry (Ochieng and Lewis, 2006), magnetic resonance imaging (Stevenson et al., 2010) and electrical resistance tomography (Williams et al., 1996; Hosseini et al., 2010; Mann et al., 2001; Stevenson et al., 2006, 2010).

In this paper, a refined approach to the use of electrical resistance tomography to analyse the suspension of the particulate phase and its resultant homogeneity is presented. In particular, homogeneity is considered in both the radial and axial direction, allowing new insights into the role of operating variables of agitation speed, solids loading and particulate size on the suspension homogeneity achieved. Moreover, an extended approach to the use of mixing indices is provided. The data suggest that complete off-bottom suspension, achieved at the critical impeller speed, is not necessarily equivalent to maximum homogeneity.

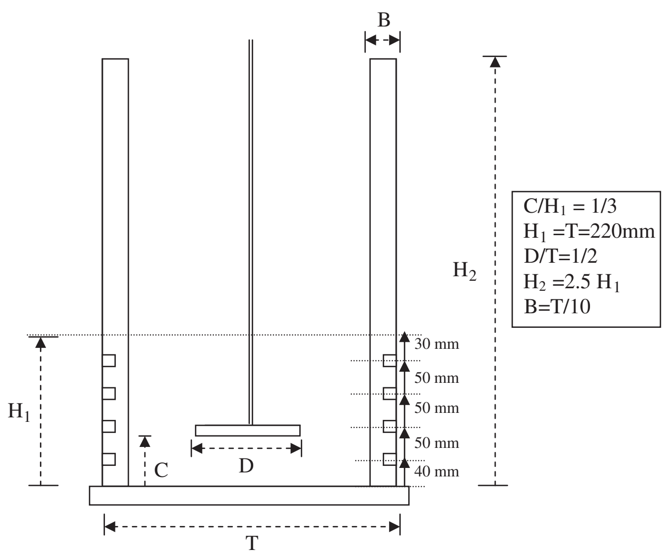

Fig. 1. Geometry of the stirred tank with electrode positions. The tank was operated at a working volume defined by height H_1 of 220 mm, with H_2 designed for future work. The aspect ratio H/T was 1. The position of the four electrode planes is also shown; plane 1 is the lowest and plane 4 the highest.

2. Materials and methods

2.1. The stirred tank reactor

A flat bottomed Perspex tank (Fig. 1, $T=22$ cm ID) was designed with 4 layers of 16 copper electrodes (Fig. 2a, 10×25 mm) spaced evenly up the side of the wall. The reactor was operated at an aspect ratio of 1.0 and was fitted with four wall-mounted Perspex baffles (Fig. 1). A Rushton impeller ($D=T/2$, clearance$=T/3$, blade length$=0.26$D, blade height$=0.21$D, disc diameter$=0.67$D) was used to agitate the suspension over a range of rotational speeds from 236 to 547 rpm. All stainless steel internal components were Teflon-coated to ensure these were non-conducting.

2.2. The model system—particulate materials and liquid phase

Quartzite particles of size fractions 106–212 μm, 425–600 μm and 600–850 μm (Table 1) and a particle density, ρ_S, of 2650 kg m^{-3} were used over a range of volume fractions (5, 10 and 20% v/v). The quartzite was suspended in a saline solution (0.1 g NaCl per litre).

Table 1
Particle statistics for the three size distributions, given in μm.

Size distribution (μm)	Mean	Mode	D_{50}	d_{90}
106–212	168	164	153	222
425–600	671	647	617	754
600–850	857	754	790	993

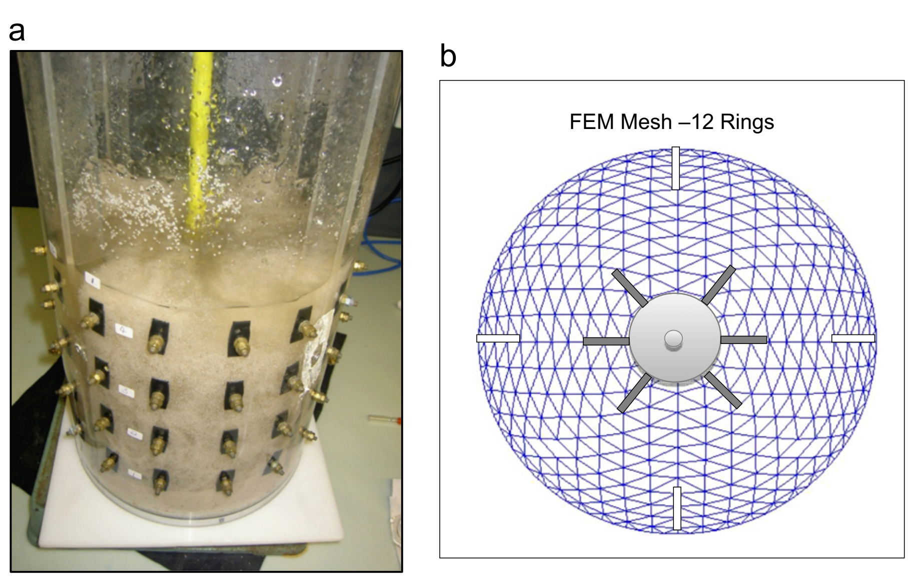

Fig. 2. (a) Baffled Perspex tank (22 cm ID) with 4 layers of 16 copper electrodes, agitated by a 6-bladed Rushton turbine, connected to ERT system and to PC. (b) 12-ring, 712 element finite element mesh showing relative positions of impeller and baffles.