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Electrical resistance tomography-assisted analysis of dispersed phase hold-up in a gas-inducing mechanically stirred vessel

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ABSTRACT

Tomographic analysis of the hydrodynamic attributes of the gas–liquid–solid mixing in a 1-l capacity stirred-tank equipped with a 4-blade gas-entrainment impeller has been used to obtain the dispersed phase hold-up distribution as a function of stirring speed (impeller Reynolds Number, Re_I) and solid particle loading. Although the liquid phase stirring was turbulent, both gas and solid flows went through different hydrodynamic regimes and experienced radial hold-up gradient over the range of impeller speed employed. Global solid phase hold-up profile exhibited a sigmoid-shape with respect to the impeller Reynolds number indicative of three solid suspension regimes across the stirring range ($1.0 \leq Re_I \leq 6.25 \times 10^4$) investigated. The solid phase hold-up distribution was adequately captured by, $\varepsilon_s = \varepsilon_{s,\max}[1-\exp(-\tau_{spp}Re_I)]^{\gamma}$ with $\varepsilon_{s,\max}$ and γ dependent on solid loading. An analogous expression was also obtained for the radial solid phase hold-up distribution and has enabled the proposition of a criterion for existence of radial transport gradient in gas-induced stirred tanks (GIST). Additionally, correlations for estimating the mixing time and power number for gas-induced mechanical agitators also gave good agreement with the empirical data.

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1. Introduction

Mechanically stirred vessels are commonly employed in the process industries for a variety of operations including pharmaceutical production, metallurgical processing, polymerisation and petrochemicals manufacturing (Ricard et al., 2005; Assirelli et al., 2008; Soleyman and Hosseini, 2009). In many cases, the liquid represents the continuous phase while the gas and solid phases constitute the disperse phase. Thus, the stirred tank performance strongly depends on the mixing efficiency of the gas–liquid and solid–liquid phases. This is especially important in catalytic processes where product yield and selectivity are key economic indicators. Superior mixing characteristics are often sought by maintaining turbulent conditions in the vessel (impeller Reynolds number, $Re_I > 10^4$), employment of multi-level impellers, baffle incorporation and other enhancement devices (Paul et al., 2004). Although there is a voluminous literature on the design of mixing vessels (Nienow et al., 1997; Neinekotter and Gericke, 2000; Tatterson, 1994), the methods often rely on 'black-box' approach with minimal consideration to the internal flow structure of the various phases. Recent studies have focussed on the application of computational fluid dynamics modelling to investigate the complex interplay of different phenomena at the local level (Ranade, 2002; Murthy et al., 2007; Kasat et al., 2008). Even so, verification of CFD simulation results by independent non-intrusive measurements is necessary to strengthen confidence in the ability of these mathematical models for practical engineering utility. It is in this respect that tomographic techniques play a complementary role in substantiating computational results and perhaps more significantly, provide a platform for building mechanistically based models since the finger-prints of various complex phenomena can be picked up by spatiotemporal changes in the physiochemical properties of the multiphase system when non-invasively probed. Process tomography employs sensory measurements rooted in electrical (e.g. capacitance, resistance and inductance modes), acoustic (ultrasound), optical and radiation (gamma, positron emission and X-ray) stimulus-response character of the system of interest. Boyer et al. (2002) have given a detailed and instructive review of various tomographic (as well as important intrusive) techniques for the measurement of multiphase flow system characteristics and conditions or criteria, which must be satisfied for deployment in meeting specific process diagnostics objective.

Although medical tomography has been well established for over two decades and credited for the significant advances made in the early detection and treatment of cancers as well as pathological foetal development, applications to industrial process systems are relatively recent as evidenced by papers in the

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proceedings of the triennial World Congress on Industrial Process Tomography (http://www.isipt.org/wcipt). The behaviour of multiphase and multi-component flow processes is reflected in the velocity profiles and phase hold-up distribution inside the vessel. Consequently, it is important to have reliable and accurate correlations between operating variables (such as, fluid flow rate, stirring speed and solid loading) and these multiphase system properties in order to optimise the design and performance for tailored applications.

Sensors for the physiochemical property of interest are typically placed around (or within) the vessel (or pipe) in an array (planar, sidewall, baffle or recirculation loop) so that real-time measurements made at different angular positions (for example, within a column at a particular plane) may be acquired and converted to electrical signals for computer processing. Using an appropriate reconstruction algorithm, the signals can be analysed to provide chronological image of the relevant phase property across the vessel cross-section and hence, on-line visualisation of the multiphase flow process (Qiu et al., 2007). Since electrical tomographic applications are characterised by fast response dynamics, rapid flow evolution may be reliably tracked. This has been used to advantage in fluidisation, bubble column and stirred tank hydrodynamics and modelling studies (Warsito and Fan, 2003; Kumar et al., 1997; Vilar et al., 2008; Ong et al., 2009).

Rodgers et al. (2009) employed an electrical impedance tomography (EIT) to monitor the performance of an industrial-scale stirred-tank reactor (200-l capacity) for the precipitation of barium sulphate. They found that the mixing curve is linked to the structure and evolution of plume during semi-batch reaction. Data arising from this investigation revealed the limitation of finite element method in the analysis of the precipitator performance. This suggests that prior or concurrent tomographic studies are essential in developing realistic numerical models for the complex hydrodynamics in a multiphase stirred reactive system. Bolton et al. (2004) have also investigated the flow pattern evolution and distribution inside a novel radial flow packed bed reactor using electrical resistance tomography (ERT). Data acquired from the 8-plane $\times$ 16-electrode sensor ERT configuration permitted conductivity measurements in the 3D-space from which local flow velocity, flow pattern uniformity and radial distributive properties were obtained. More recently, Razzak et al. (2009a) determined the phase hold-up distribution in a gas–liquid–solid circulating fluidised bed using ERT. They observed that the radial distribution for solid hold-up has a minimum in the central region and increased towards the wall while an opposite trend was observed for the gas hold-up.

The quality of fluidisation in both lab-scale and industrial size gas–solid fluidised bed dryers has also been studied as a function of solid loading, particle size and density using gamma-ray tomography, GRT (Patel et al., 2008). Similarly, Guida et al. (2009) have examined the mixing of concentrated suspension of coarse glass particles in a stirred tank with the aid of positron emission particle tracking. Velocity field and spatial distribution of both liquid and solid phases were obtained. While this brief review of representative tomographic investigations of multiphase flow processes demonstrate the merits of non-invasive techniques for clearer understanding of the mechanisms involved in gas–liquid–solid hydrodynamics, it is useful to provide quantitative correlations between multiphase flow metrics (phase hold-up distribution, degree of phase homogenisation or uniformity, mixing time, etc.) and antecedent hydrodynamic operating variables suitable for tunable design objective or optimal process operation especially in the pharmaceuticals, environmental and clean energy production industries where mechanically stirred vessels are commonly used. Gas-induced stirrer is an especially attractive mode of agitation for many gas–liquid–solid reactive systems where low gas conversion per pass may be detrimental to process efficiency.

Gas-inducing impeller, which allows recirculation of gas from the headspace back into the liquid, is attractive for reaction systems with the possibility of low gas conversion per pass such as in Fischer–Tropsch reaction and deep liquid phase oxidation of organics. In fact, gas-inducing mechanically stirred tank (GIST) enhances mixing performance and better inter-phase mass transfer compared to a conventional agitator at similar speeds while requiring no equipment external to the reactor (Murthy et al., 2008). For over 2 decades, various aspects of gas-inducing stirred tanks have been examined in the literature. Joshi and collaborators (1979, 2007, 2008) as well as Forrester et al. (1997) have studied the design and operational characteristics of GISTs. They proposed equation for determining the value of the critical impeller speed for gas sparging and optimal blade geometry for high performance mixing. Jafari and Mohammadzadeh (2005) also reported that mixing in the GIST is the closest to that of an ideal CSTR although it may be plagued by large dead zones (up to 16.7%) at low liquid flow rates and significant bypassing (as high as 10%) at high liquid flow rates. Mixing time and homogenisation energy analysis were based on invasive RTD method. Ford et al. (2008), have, nonetheless, employed X-ray computed tomography to obtain qualitative understanding of the recirculation regions. They only provided global gas phase hold-up correlation, which limited application to the narrow range of impeller speed (350–700 rpm) used.

Conway et al. (2002) and Hichri et al. (1992) investigated gas–liquid mass transfer in gas-induced stirred tank slurry reactors. Hampel et al. (2007) and Hristov et al. (2008) employed gamma-ray tomography to investigate the two-phase flow in stirred tank reactor using gas-inducing 6-blade turbines. Due to additional complexities associated with three-phase flow, there is a paucity of information on the hydrodynamics and mixing in gas–liquid–solid GISTs. In view of the stated advantages of the GIST over conventional spargers and recycle systems, especially in relation to commercial gas–liquid–solid operations where low gas conversion per pass or hazardous gases are anticipated, it is essential to provide reliable correlations usable for design and scale-up based on non-intrusive systems characterisation such as that offered by process tomography.

In this paper, we present an ERT analysis of for gas–liquid–solid mixing in such an agitator. Existing design correlations are based on information collected from intrusive techniques such as direct residence-time distribution measurements (Ramachandran and Chaudhari, 1983; Tatterson, 1994) and in many cases, applicable to a narrow range of operating variables. Specifically, the goals of this investigation were to obtain tomographically guided correlations for solid- and gas-phase hold-ups as a function of stirring speed and solid loading over sufficiently wide range to cover most practical conditions. Moreover, we provide an expression for the spatial variation of the local phase hold-up within the mixed tank since this will be necessary in subsequent reactor analysis.

2. Experimental details

Electrical resistance tomography is well-suited for systems where the continuous phase is electrically conductive while the dispersed phase is non-conducting. The continuous phase in this study was water with air and alumina particles, the dispersed phases. Nanopure water (obtained from Barnstead Diamond NANOPure water unit) was used in all runs while alumina particles (Saint-Gobain Norpro Corporation) with particle size range 60–90 μm having a BET area and pore volume of 210 $m^2 g^{-1}$ and 0.69 ml g^{-1}, respectively, were used. A stirred-tank made of clear

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