CHEMICAL ENGINEERING RESEARCH AND DESIGN 111 (2016) 223–242

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Characterization of solid–liquid settling suspensions using Electrical Impedance Tomography: A comparison between numerical, experimental and visual information

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ARTICLE INFO

Article history:
Received 3 November 2015
Received in revised form 12 May 2016
Accepted 16 May 2016
Available online 21 May 2016

Keywords:
Electrical Impedance Tomography
Particle distribution profiles
Solid–liquid suspensions
Mixture model
Drag models

ABSTRACT

To address the limitation of traditional characterization techniques, over the past two decades, non-invasive monitoring tomography techniques have been employed in the study of multiphase systems. Amongst them, electrical tomography offers several advantages when compared with the traditional methods, such as providing information on the boundaries between mixture components, flow regimes, concentration distribution in the cross section of conveying pipes and mixing zones distribution in stirred tanks, amongst others, resulting in a better understanding of the monitored process and as a means of validating physical models.

With the present study the objective was to validate experimental particle distribution profiles attained with an EIT apparatus, for two different average particle sizes, 0.15 and 0.5 mm, and increasing volumetric concentration up until 11.0% (v/v), in a horizontal flow pipe cross section. To this end, experimental particle distribution profiles from a Sampling Probe (SP), numerical particle distribution profiles obtained using the Mixture Model coupled with a High Reynolds k–ε turbulence model and visual inspection served as a comparison basis (Goeree et al., 2016; Silva et al., 2015). Analysis of the resulting 1D particle distribution profiles from both experimental techniques and numerical data shows a good agreement, thus, demonstrating the potential of the EIT in the characterization of solid–liquid suspensions flow for the range of particle concentrations and sizes tested.

1. Introduction

Solid–liquid suspensions flows under turbulent conditions are present in a wide range of industrial processes which are seldom optimized as a result of an inefficient design. This inefficiency results from both a poor understanding of the suspension hydrodynamics and from the use of empirical correlations applied to predict the behaviour of suspension flow, thus, the ability to understand suspension hydrodynamics is a crucial issue for better control and monitor of operations in process plants. On-line data acquisition is pivotal for high quality products, smooth plant operation, economical

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http://dx.doi.org/10.1016/j.cherd.2016.05.013

Nomenclature

ε [m^2/s^3]	turbulent dissipation rate
η	normalized electrical conductivity difference
κ	Von Kármán constant
μ [Pa s]	mixture dynamic viscosity
μ_c [Pa s]	dynamic viscosity of the continuous phase
μ_d [Pa s]	dynamic viscosity of the dispersed phase
μ_T [Pa s]	turbulent dynamic viscosity
ρ [kg/m^3]	mixture density
ρ_c [kg/m^3]	continuous phase density
ρ_d [kg/m^3]	dispersed phase density
σ_T	particle Schmidt Number
τ_{Gm} [N/m^2]	turbulent and viscous stresses
σ_0 [μs/cm]	NaCl reference electrical conductivity
σ_m [μs/cm]	solid-liquid suspension electrical conductivity
σ_w [μs/cm]	water electrical conductivity
ϕ_c	continuous phase volumetric fraction
ϕ_d	dispersed phase volumetric fraction
ϕ_o	initial dispersed phase volumetric fraction
ϕ (z)	EIT calculated dispersed phase volumetric fraction
A_σ	area under the normalized electrical conductivity curve
B	wall function constant
C_D	drag coefficient
D_{md} [m^2/s]	turbulent eddy diffusion
d_p [m]	particle diameter
F	volume forces
g [m s^{-2}]	gravitational acceleration
I_T	turbulence intensity
k [m^2/s^2]	turbulent kinetic energy
L_i [m]	inherent dissipation length scale
L_T [m]	turbulence length scale
m_{dc} [kg/m^{3}s]	mass transfer ratio between phases
p [Pa]	pressure
Re	flow Reynolds number
Re_p	particle Reynolds number
S_s	ratio between the solids and fluid densities
u [m s^{-1}]	mixture velocity
u^T [m s^{-1}]	transpose of the mixture velocity
u_c [m s^{-1}]	continuous phase velocity
u_d [m s^{-1}]	dispersed phase velocity
u_{slip} [m s^{-1}]	the relative velocity between phases

management of wastes and resources as well as for design improvement of the flow and pumping equipment (Lee et al., 2005). Although it may seem of straightforward application in theory, the practical implementation is quite complex. A number of discrete sensors distributed throughout critical locations of the plant sums up the traditional course of action for monitoring and/or controlling the plant operation. As a consequence from this oversimplified solution, an invariable loss of key information of both physical and chemical processes occurs in the manufacturing process.

To address this limitation of traditional methods, over the past two decades, process tomography techniques have been developed (Beck and Williams, 1996; Crowe, 2005). Initially designed for non-invasive monitoring of multiphase phenomena present in petroleum pipelines, it promptly moved to other applications such as batch reactors, mixing vessels, hydraulic and pneumatic conveying (Dyakowski and Jaworski, 2003; Sapkota et al., 2015; Faraj et al., 2015; Wang et al., 2015). Electrical tomography offers several advantages when compared with the traditional methods, such as providing information on the boundaries between mixture components, flow regimes and velocity fields, concentration distribution in the cross section and mixing zones distribution in stirred tanks, amongst others, resulting in a better understanding of the monitored process and possessing the capacity of being used as a means of validating physical models. Through the manipulation of data obtained from sensors placed around the section of interest, tomographic images are reconstructed using a computational algorithm. These images are then analyzed and the data obtained is incorporated in the improvement of both design strategies and numerical models. Although most of the publications in the literature of electrical tomography are in an academic environment, slowly they are transferring to industrial plants: Electrical Capacitance Tomography (ECT) has been implemented in several industrial fields, ranging from hydrodynamics of gas–liquid packed beds (Hamidipour and Larachi, 2010), measuring solids concentration in a cyclone separator (Sun et al., 2008), monitor flow regimes during hydraulic and pneumatic conveying (Arko et al., 1999; Beck et al., 1993; Zhu et al., 2003), study of low water fraction foams (Bennett et al., 2002), to combustion phenomena in an internal combustion engine (Vilar et al., 2008), just to name a few. Electrical Resistance Tomography (ERT) has had some applications in the visualization of swirling flows (Wang et al., 2003), in the improvement of a differential pressure flow meter (Venturi type) in two-phase measurements (Meng et al., 2010), 3D imaging of concrete (Karhunen et al., 2010), controlling the emulsion process of a sunflower oil/water mixture (Boonkhao et al., 2011), investigation of the influence of the reactor geometry on multiphase processes typical of pharmaceutical industries (Ricard et al., 2005) amongst others. In a more indirect way, this technique was also used to provide valuable data for the refinement of CFD models in slurry mixing (Williams et al., 1996). Electrical Impedance Tomography (EIT) has been employed, for instance, in the study of paste extrusion (West et al., 2002), in the mixing of two miscible liquids in a turbulent flow in a papermaking trump-jet system (Kourunen et al., 2008), in the monitoring of 3D drug release as a function of time (Rimpiläinen et al., 2010) and for the visualization of conductivity in a cell culture (Sun et al., 2010). More detailed depiction of electrical tomography applications in the scope of industrial chemical engineering can be found in the literature (Rasteiro et al., 2011; Tapp et al., 2003; Dyakowski et al., 2000).

With the advent of computational modelling techniques and ever evolving computer hardware, the traditional approaches are being refined or even replaced, providing scientists, engineers and equipment designers with an enhanced foreseeing capability and lack of restrictions to adjust process conditions to better suit their demands (Massoudi, 2010). While CFD single phase codes are well established in the literature, for multiphase flows they are still an open problem (Balachandar and Eaton, 2010). In two-phase modelling it is very important to depict interphase forces as accurately as possible (Pang and Wei, 2011; Goeree et al., 2016), particularly in settling particle flows. Moreover, the complexity in horizontal solid-liquid particle flow stems from the different flow regimes that may occur (Rojas and Sáez, 2012). In the literature, a numerical study comparing both the Mixture model