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Analysis of mixing in an aerated reactor equipped with the coaxial mixer through electrical resistance tomography and response surface method

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ABSTRACT

Mixing characteristics of an aerated coaxial mixer composed of an anchor and a central impeller was investigated using the non-invasive flow visualization technique called electrical resistance tomography (ERT). Corn syrup solutions with different viscosity were used as the viscous Newtonian fluids. Two coaxial configurations were considered: the anchor – PBD (a pitched blade downward pumping impeller) and the anchor – PBU (a pitched blade upward pumping impeller). In this study, the effects of central impeller types, speed ratios (central impeller speed/anchor speed), rotation modes, gas flow rates, and viscosity on the mixing time and power uptake were explored. It was found that in the presence of gas, the PBU-anchor coaxial combination in co-rotating mode exhibited shorter mixing times and lower power consumption than the PBD-anchor. Experiments demonstrated that the effect of aeration on the mixing time was a function of hydrodynamic regimes occurring in the tank. Using the response surface method, an effort was made to develop a quadratic model as a function of central impeller speed, anchor speed, gas flow rate, and viscosity for predicting the mixing time. Three-dimensional response surfaces were plotted to understand the main and interaction effects of these factors.

1. Introduction

Mechanically stirred vessels are indispensable parts of variety of process industries for single phase or multiphase flow agitation including gas–liquid and gas–liquid–solid mixings. Two phase gas–liquid systems have attracted considerable attentions in many technologies especially biochemical engineering. The reason is attributed to the utilization of a gas phase in many fermentation processes. In such complex multiphase processes, agitation must provide not only the highest mass transfer rate, which is related to the gas holdup, but also the specified degree of homogeneity in the shortest possible time. Insufficient mixing in multiphase processes causes continuous variations in the surrounding environment of micro-organisms due to the formation of oxygen and nutrient segregation zones leading to the rapid strain degradation and a decreased process output (Espinosa-Solares et al., 2002; Lamberto et al., 1996; Vrabel et al., 2000). The accessibility and distribution of the nutrient throughout the fermenters are essential and can significantly alter the metabolic pathway and the biological product distribution. These segregation zones must be eliminated since they act as barriers to agitation processes and give rise to mixing time and undesired by-products.

Over the years, several approaches have been proposed to eliminate segregation regions (Espinosa-Solares et al., 2002; Lamberto et al., 1996; Foucault et al., 2004, 2005, 2006; Pakzad et al., 2008a, 2008b, 2008c, 2013a, 2013b). As an illustration, increasing the impeller rotational speed is employed in order to prevent the development of the aforementioned undesired

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Nomenclature

Parameter	Unit
D	Impeller diameter, m
D_c	Central impeller diameter, m
D_a	Anchor diameter, m
D_s	Sparger diameter, m
N	Impeller speed, s^{-1}
N_c	Central impeller speed, s^{-1}
N_a	Anchor impeller speed, s^{-1}
P_{gtot}	Total gassed power, W
M	Torque, $N.m$
X_1	Coded value of central impeller speed,s^{-1}
X_2	Coded value of anchor speed, s^{-1}
X_3	Coded value of gas flow rate, m^3s^{-1}
X_4	Coded value of the viscosity, Pa.s
Y	Response function, s
t_m	Mixing time, s
T	Tank diameter, m
Q_g	Gassing rate per volume, s^{-1}
Greek letters	Unit
μ	Newtonian liquid viscosity, Pa.s
ρ	Newtonian liquid density, kg/m^3

Dimensionless numbers

Fl_g	Gas flow number (-)
Re	Reynolds number (-)
N_p	Power number (-)
R_N	Speed ratio (-)

Abbreviations

PBU	Pitched blades upward pumping
PBD	Pitched blades downward pumping
ERT	Electrical resistance tomography

Subscripts

g	Gas
l	Liquid
a	anchor
c	central impeller
s	sparger

zones. The basic drawback of this approach is excessive power uptake of the impeller especially in highly viscous fluids that cause mechanical damage. Using high rotational speed is also impractical in many biotechnological applications, where substances namely micro-organisms are shear-sensitive, and fast stirring leads to a reduction in productivity (Lamberto et al., 1996). It should be mentioned that, when the shear sensitivity of the micro-organisms is defined as a significant factor in the design of the most efficient bioreactor, the multiple-impeller agitated tanks become more favorable. Although the traditional mixing systems with multiple impellers placed on a same shaft provide a better gas dispersion, higher gas residence time and gas holdup in comparison with the single impeller ones, they are not effective for highly viscous Newtonian and non-Newtonian fluids. Therefore, coaxial mixing vessel can be a favorable approach to tackle the aforementioned problems. The coaxial mixers have been suggested by the previous researchers (Bonnot et al., 2007; Foucault et al., 2004, 2005, 2006; Pakzad et al., 2008a, 2013a; Thibault & Tanguy, 2002) for the agitation of highly viscous Newtonian and non-Newtonian fluids. Thus, the use of the coaxial mixers appears to be a promising way to eliminate oxygen and nutrients segregated regions inside the vessels. The reason is related to the synergistic fluid dynamic effects of two independently driven agitators rotating at different speeds. However, little information is available regarding the aerated coaxial mixers equipped with a centered open impeller in conjunction with a close clearance anchor. In such a system, anchor acting at low speed is primarily responsible for cleaning up the tank wall and returning back the bulk fluids that are stacked away from the centered impeller. Open impellers, which are generally placed in the center of the tank, operate at high speed to produce intensive shear. In such complex aerated systems, the goals of impellers must be circulation, homogenization, and promotion of gas hold-up throughout the mixing vessel. Many studies have shown that axial flow impellers provide considerable advantages over radial impellers in the presence of gas (Cronin et al., 1994; McFarlane & Nienow, 1996; Nienow, 1998; Machon & Jahoda, 2000; Vrabel et al., 2000). It has been demonstrated that axial up-pumping agitators outweigh down-pumping ones in terms of power and torque instabilities in the aerated systems (Aubin et al., 2001; Hari-Prajitno et al., 1998; Vrabel et al., 2000). Therefore, in this work, a combination of an axial impeller, pitched blade turbine, with anchor as a coaxial agitated system was considered.

Several factors such as level of homogeneity and power consumption must be considered in designing an efficient mixing system. Mixing time is denoted as a time required to reach a predefined level of homogeneity (Espinosa-Solares et al., 2002). Using mixing time, useful information can be obtained about flow inside the vessel. The shorter the mixing time the more efficient the blending becomes. In the absence of gas, only a very limited amount of data demonstrated that coaxial systems operating in co-rotating mode with Newtonian and non-Newtonian fluids exhibit better performance in comparison to the ones in counter-rotating mode and single impeller systems (Rudolph et al., 2007; Foucault et al., 2006; Bao et al., 2011; Pakzad et al., 2008a, 2008b, 2008c, 2013a). However, no data have been reported on the mixing time of the aerated coaxial systems due to the complications arising from complexity of the hydrodynamics and use of different types of agitators and criteria. Hashemi et al. (2016) studied the bubble characteristics such as number of bubble size classes, contribution of each class of bubble in the overall gas holdup, bubble size distribution, and local gas holdup within the aerated coaxial mixing vessel by means of the DGD (dynamic gas disengagement) coupled with ERT technologies.

For the single-shaft aerated mixing vessels, mixing time as a function of the power drawn has been studied by many researchers (Nienow & Wisdom, 1974; Van't Riet, 1976). However, much less research has been carried out to define the effects of aeration on the mixing time and it is still an open question. Some studies demonstrated that aeration decreases the mixing time (Vasconcelos et al., 1995), while others (Machon & Jahoda, 2000) indicated that mixing time can be enhanced and reduced by gassing, according to the dominance of gas flow rate or impeller rotational speed. The gas–liquid flow pattern plays a crucial role in the aerated vessels. When the gas is distributed into the vessel, different flow patterns develop depending on the gas flow rates and impeller rotational speeds. At lower impeller speeds or higher gas flow rates, the flow pattern inside the vessel is controlled by the gas flow and therefore the impeller is unable to disperse the gas effectively. This condition is called flooding regime.