CHEMICAL ENGINEERING RESEARCH AND DESIGN 108 (2016) 55–68

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Experimental investigation of the mixing of viscous liquids and non-dilute concentrations of particles in a stirred tank

Manon Lassaigne, Bruno Blais, Louis Fradette*, François Bertrand*

Research Unit for Industrial Flow Processes (URPEI), Department of Chemical Engineering, Polytechnique Montreal,
P.O. Box 6079, Station CV, Montreal, Canada H3C 3A7

ARTICLE INFO

Article history:
Received 18 August 2015
Received in revised form 3 December 2015
Accepted 6 January 2016
Available online 5 March 2016

Keywords:
Solid–liquid mixing
Viscous fluid
High solids loading
Stirred tank
Just suspended speed

ABSTRACT

Despite the importance for the process industry of solid–liquid mixing operations involving viscous liquids and high solids concentrations, most of the reported results have been obtained in the turbulent regime with low solids loadings. In this work, the suspension of non-dilute concentrations of spherical particles in viscous liquids is investigated through the determination of the just-suspended speed N_{js}, the homogenization speed N_H and the homogenization time t_H. The pitched blade turbine, which is a common and suitable agitator for the suspension of solids in the turbulent regime, is chosen. N_{js} is obtained using the pressure gauge technique, and N_H and t_H via electrical resistance tomography. The impact of the particle diameter d_p, the solids mass concentration X_w, the liquid viscosity μ, and the impeller diameter D and off-bottom clearance C are assessed. In particular, the effect of d_p and μ on N_{js} are observed to be in contradiction with the Zwietering correlation, which was derived in the turbulent regime. This is attributed to the hydrodynamics and mechanisms prevailing in the laminar and early transitional regimes, which are similar to those for the erosion of a particle bed. This also explains the discrepancies between our experimental values and the values of N_{js} predicted by the Zwietering correlation. Also, increasing X_w affects N_{js} in a more complex manner than what is predicted by this correlation. Finally, our results indicate that particle bed erosion is the dominating phenomenon to consider both to suspend the particles and achieve a uniform suspension in the tank.

1. Introduction

Solid–liquid mixing in agitated vessels is a common unit operation that plays a key role in the chemical process industry. In many of these operations, such as in chemical reactors containing a solid catalyst, the main objective is to reach a certain level of homogeneity, and to maximize the contact area between the two phases. Although most of the literature on solid–liquid mixing relates to the turbulent regime (Atiemo-Obeng et al., 2004; Oldshue, 1961), for the cosmetics, food and pharmaceutical industries, for instance, the systems usually involve viscous, possibly non-Newtonian, liquids and large concentrations of solids to suspend. The complexity arising from both the geometry of the vessel and the rheology of the suspensions can lead to the formation of unfamiliar flow patterns, and the estimation of the key parameters remains unclear. In particular, the Zwietering correlation (Zwietering, 1958), as further discussed below, has several limitations for high solids loadings and laminar systems, which may lead to poor predictions of the just-suspended speed N_{js}, causing important quality deterioration and large economic losses (Ibrahim and Nienow, 1999; Paul et al., 2004). Consequently, it

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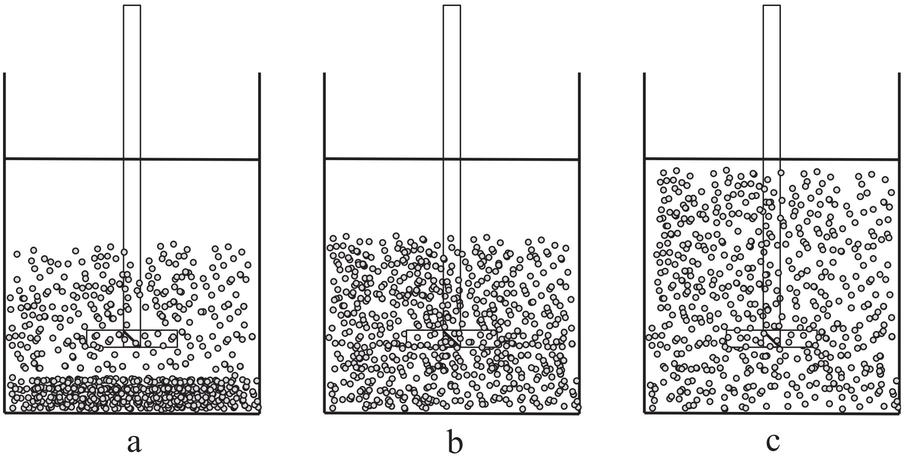
* *Corresponding authors.*
E-mail addresses: louis.fradette@polymtl.ca (L. Fradette), francois.bertrand@polymtl.ca (F. Bertrand).

http://dx.doi.org/10.1016/j.cherd.2016.01.005


a

b

c

Fig. 1 – States of suspension: (a) on-bottom suspension, (b) off-bottom suspension, and (c) homogeneous suspension.

is necessary to improve our understanding of the influence of the geometry, fluid and solid properties, and operating parameters on the flow dynamics of this type of solid–liquid mixing operations.

For solid–liquid mixing in stirred tanks, the degree of suspension required depends on the type of operation. On-bottom suspension (Fig. 1a), in which some of the particles rest on the bottom of the tank can be, for instance, sufficient for highly soluble solids dissolution (Atiemo-Obeng et al., 2004). To maximize the solid–liquid interfacial surface area and therefore the mass transfer, it is usually necessary to operate at complete off-bottom suspension state, as illustrated in Fig. 1b (Ayranci et al., 2013). This condition corresponds to the just suspended speed N_{js}, and has been defined by Zwietering as the "impeller speed at which no particle remains stationary at the bottom of the tank for more than 1 or 2 seconds" (Zwietering, 1958). He proposed the following correlation:

$$N_{js} = S\left(\frac{g(\rho_s - \rho_l)d_p}{\rho_l}\right)^{0.45} \frac{\nu^{0.1}X^{0.13}}{d_p^{0.25}D^{0.85}} \tag{1}$$

where g is the gravity, ρ_s and ρ_l the solid and fluid densities, ν the kinematic viscosity, and X the solids content (solid mass/liquid mass $*$ 100). Other parameters that affect N_{js} and that are related to the geometry of the mixing system are included in the constant S: the tank diameter, the impeller type and off-bottom clearance, the tank bottom shape, and the baffle off-bottom clearance (Atiemo-Obeng et al., 2004).

N_{js} is an essential parameter for the design of stirred tanks, which explains the considerable body of research on this topic in the last decades. However, most of the articles referring to the minimum agitation speed for complete suspension relate to the turbulent regime and low concentrations of solids, i.e. inferior to 2 wt% according to Ayranci et al. (2013). Only a few papers have pointed out the unsuitability of the existing correlations for viscous fluids and high solids concentrations (Ayranci and Kresta, 2013; Grenville et al., 2015; Ibrahim and Nienow, 1999, 2009; Tamburini et al., 2014).

A study performed in the transitional regime using a 1 Pa s fluid showed that the Zwietering correlation may over-predict N_{js} by more than 90% (Ibrahim and Nienow, 1999). These authors reported that, up to 0.01 Pa s, the Zwietering correlation is applicable, although there are considerable limitations at small values of the Reynolds number (Re). Besides, above solids contents of 2 wt%, the particle–particle interactions increase and the suspension behavior may deviate from that predicted by the Zwietering correlation (Ayranci and Kresta, 2011). This comes from the fact that the effect of solids loading is complex and that, in particular, the exponent on X depends on the type, number and position of the impeller in the tank (Wu et al., 2001). Grenville et al. (2015) state that the Zwietering correlation does not account correctly for the effect of μ, $\Delta\rho = \rho_s - \rho_l$ and scale on N_{js}. They propose a new correlation based on experiments and covering a large range of viscosities in the transitional regime. Another source of uncertainty is the constant S in the Zwietering correlation, which is difficult to determine. While it is known to depend on T, D and C (Atiemo-Obeng et al., 2004), it has been reported that the particle diameter and type are also of great importance (Ayranci and Kresta, 2011).

Most of the experimental work done so far to determine N_{js} has relied on visual observation of the movement of the particles at the bottom of the tank using a mirror (e.g. Zwietering, 1958). Some work has also used observations from the side of the vessel (Kraume, 1992). Though relatively simple to implement, this method is subjective, and gives no information on the fraction of solids suspended at an impeller velocity below N_{js} (Kasat and Pandit, 2005). It is also limited to solids concentrations lower than 2 wt% and to the use of a transparent vessel, which is uncommon for large-scale systems. Different alternate approaches have been developed to overcome these limitations. One of them is the pressure gauge technique (PGT). This technique is based on the measurement of the pressure at the bottom of the tank and can be applied on double- and three-phase systems over a large range of solids concentrations (Brucato and Rizzuti, 1997; Micale et al., 2000, 2002; Tamburini et al., 2011b). For a thorough review on N_{js} and its characterization, the reader is referred to Kasat and Pandit (2005), Jafari et al. (2012a), and Tamburini et al. (2012).

A suspension is said to be homogeneous when the distribution and dispersion of the particles are uniform in the tank (Fig. 1c). When this condition is reached, the impeller speed is called the homogenization speed N_H.

Along this line, the homogenization time t_H corresponds to the time necessary for the agitator to lift the particles, distribute them in the entire tank and obtain the maximum degree of homogeneity. It depends on the impeller speed and, for this reason, it is measured at $N = N_H$. This time is different from the mixing and the circulation times usually encountered in the literature: the former gives the time for an added volume of fluid to be uniformly mingled in a second fluid (Brown et al., 2004), and the latter represents the time taken for