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Complementary methods for the determination of the just-suspended speed and suspension state in a viscous solid–liquid mixing system

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ABSTRACT

A poor understanding of mixing dynamics may lead to major economic losses in numerous industries due to poor yields and waste of raw materials. Then processes can be optimized through a better understanding of solid–liquid mixing dynamics.

Previous studies have characterized the suspension of solid particles in a viscous medium using a standard high shear impeller (a pitched-blade turbine or PBT) and have measured the fraction of suspended particles using the pressure gauge technique (PGT). Since the PGT cannot be applied in a straightforward way to close-clearance impellers, we developed a novel technique based on the PGT to determine the fraction of suspended particles in a system using a close-clearance impeller such as a double helical ribbon (DHR).

We studied a solid–liquid suspension in the laminar and transitional regimes with high particle loadings and a DHR. Since the dynamic pressure cannot be subtracted from the total pressure determined by the PGT, we developed two alternative methods. The first was the pressure difference method, which we used to determine a range of speeds where N_{js} is located. The second was the sedimentation-based method which we used to accurately quantify N_{js} and effectively eliminate the dynamic pressure. Their pertinence and applicability were demonstrated.

1. Introduction

A wide range of solid–liquid mixing based processes are used in the pharmaceutical, cosmetic, food, and mineral industries. These processes require an in-depth understanding of the mechanisms that govern the suspension of solid particles and that are highly dependent on the mixing regime. For example, Ayranci et al. (2012) showed that the mean flow as well as small eddies in the turbulent regime play a role in the suspension of particles. They also showed that the relative importance of these two factors is a function of the impeller size (Ayranci et al., 2012). Furthermore, Lassaigne et al. (2016) recently showed that the suspending mechanisms in laminar regimes are different from those in turbulent regimes.

The just-suspended speed has been defined as a mixing requirement for "achieving and maintaining off-bottom suspension of solids" (Paul et al., 2004). Zwietering (1958) described it as the speed at which all particles do not remain motionless on the bottom of the mixing tank for more than 1–2 s (Zwietering, 1958) and proposed a correlation for determining N_{js} based on experimental measurements. However, this correlation has several limitations, mainly for systems involving high solid loadings (over 2 wt%), operating in the laminar or the transitional regimes, and for unimodal slurries. Furthermore, the N_{js} constant (S) must accurately match the geometry of the system (Ayranci and Kresta, 2014). Alternative correlations with broader applicability have since been proposed (Lassaigne et al., 2016; Bujalski et al., 1999; Grenville et al., 2010; Ibrahim and Nienow, 1999) using different methods for

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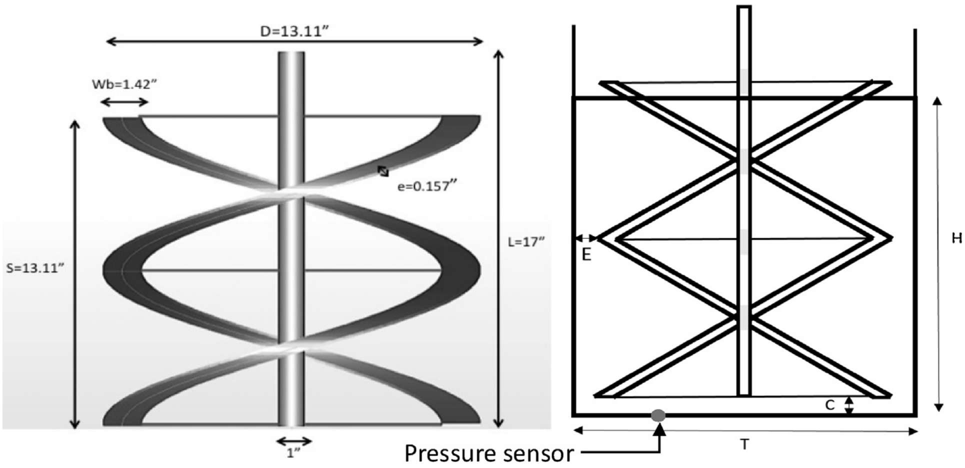

Fig. 1 – Illustration of the experimental mixing tank, including the double helical ribbon (DHR), the vessel, and the pressure sensor.

experimentally measuring N_{js}. Comprehensive reviews of these methods are available in Tamburini et al. (2014) and Jafari et al. (2012).

Flow regimes dictate the dominant mechanism for solid suspensions. However, little is known about solid suspensions in laminar and transitional regimes. One study, (Ibrahim and Nienow, 1999) broadly examines the effects of different impeller types on the just-suspended speed for a large range of Reynolds numbers. Another, (Lassaigne et al., 2016) on solid–liquid mixing using a PBT, showed that increasing the particle diameter, the solid volumetric fraction and the viscosity of the liquid causes a decrease in N_{js}. These results suggested that shear stress and the pressure applied at the surface of the particles suspend the particles, much like the erosion mechanism described by Leighton and Acrivos (1986). Although this may be true for a PBT, it is likely not the case for all types of impellers (axial, radial, mixed and close-clearance). Few studies have been made on the suspension mechanisms and just-suspended speed of close clearance impellers. To our knowledge, there is the paper published by Ibrahim et al. (2015) that discusses the effects of various parameters on the just-suspended speed of fine particles in the turbulent regime. However, effects of these parameters may be different in the laminar regime. Since viscous fluids are not easily pumped, it is generally preferable to use a close-clearance impeller that is designed to turnover and positively displace such fluids (Paul et al., 2004). Lassaigne et al. (2016) investigated the use of a PBT for suspending solid particles in laminar and transitional flow regimes, but close-clearance impellers have never been studied in a similar system. The objective of this work is then to investigate the suspension of solid particles using such an impeller.

2. Methodology

2.1. *The pressure gauge technique*

There are numerous techniques for measuring N_{js}, such as the concentration method (Bourne and Sharma, 1974; Musil, 1976) or the radioactive particle tracking method (Rewatkar et al., 1991), but since they all suffer from limitations, none of them is clearly superior (Micale et al., 2002). The pressure gauge technique (PGT), which was introduced by Micale et al. (2002) and Brucato et al. (1997), is a simple and accurate method for calculating N_{js} that is based on determining the fraction of suspended solids using pressure measurements at the bottom of the vessel.

When the impeller is at rest, the pressure at the bottom of the tank is solely the hydrostatic pressure created by the weight of the liquid head. However, once the impeller is set into motion, the pressure at the bottom of the tank changes to encompass the dynamic and hydrostatic pressures. When the suspension process begins, the apparent density of the liquid increases when the weight of the particles is transferred to the liquid. This weight transfer results in an increase in the hydrostatic pressure. Once all the particles are suspended, the apparent density remains constant as does the hydrostatic pressure. The fraction of suspended particles can thus be obtained from the variation in the hydrostatic pressure. However, the increase in impeller speed also affects the dynamic component of the pressure. A second order polynomial curve can be fitted to the pressure data, past the inflexion point based on the procedure introduced by Micale et al. (2002) to subtract the effect of the dynamic pressure on the total pressure and thus deduce the variation in the hydrostatic pressure from which the fraction of suspended particles is calculated. N_{js} is then obtained using the fraction of suspended particles as a function of impeller velocity. An example of such a curve is shown in Fig. 3.

While the PGT is commonly used in the turbulent regime to study mixed, axial, and radial impellers. Lassaigne et al. (2016) are the only researchers to have used the PGT in the laminar and transitional regimes. However, close-clearance impellers have never been investigated in turbulent, laminar, or transitional regimes.

3. Experimental set-up

Experiments were performed in a flat-bottomed, cylindrical, transparent tank equipped with a double helical ribbon (DHR). The schematic shown in Fig. 1 and described in Table 1 present the experimental set-up.

In this set-up, the fraction of suspended solids is determined using a sensor (Freescale: MPX5010DP), with a 5%

Table 1 – Dimensions and ratios to tank diameter of the experimental setup.

Dimension	Size (in.)	Ratio (dimension/T)
T	14.37	1
H	14.37	1
C	1.76	8.2
E	0.63	22.8
D	13.11	1.1
S	13.11	1.1
L	17	0.8
Wb	1.42	0.1
e	0.157	0.01