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Estimating Just Suspension Speed for Stirred Reactors Using Power Measurement

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ABSTRACT

A simplified mathematical model was developed to predict the just suspended speed, N_{JS} in a solid-liquid system by analysing the net impeller power consumption to suspend solid particles. A fully baffled tank with an internal diameter of 400mm equipped with a standard Rushton turbine with a diameter of $D=T/3$ (133mm) was used in this work. Glass beads were used as the solid phase and distilled water was used as the liquid phase. Solid loadings were varied within the range of 0-27 wt%. Power consumption was measured using the shaft torque method. The predicted N_{JS} values were in a good approximation to the experimental values using the Zwietering's criterion with a deviation of 2 – 10%. The deviation was lower for higher solid concentrations.

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1. Introduction

Suspension of solids or processing of slurry, where particles are suspended in a continuous liquid phase in stirred vessels is common in chemical, paints, ceramics, cosmetics and pharmaceutical industries. Recently, multiphase systems also include biochemical, biopharmaceutical and various other specialised chemical industries. The most important work on solid suspension in stirred vessels was conducted by Zwietering in (1958) (Zwietering, 1958), introduced the term 'critical speed' to just suspend solids (just suspension speed or N_{JS}). The work is still cited until today. Zwietering's description for "just suspension" where there are no solid particles

staying on the bottom of the stirred vessel longer than 1 to 2s is still the most widely used reference for solid suspension. The interest for N_{JS} is mainly driven by the need to achieve the "optimal" speed or energy consumption to achieve the designed process efficiency, and hence achieving lower operating costs. Here, the term "optimal" is typically correlated with N_{JS} as the lowest one-solution-fits-all operating speed that meets the mass- and energy-transfer requirements of a process.

$$N_{JS} = S \vartheta^{\alpha} \left[\frac{g_c(\rho_s - \rho_l)}{\rho_l} \right]^{\beta} d_p^{\gamma} D^{\delta} X^{\theta} \quad (1)$$

Nomenclature

D	Impeller diameter, m
d_L	a distance from the motor to the central rod, m
d_p	Particle diameter, m
g	acceleration of gravity force, 9.8 m/s ²
H	Liquid height, m
m	mass defined by the load cell, kg
N	Impeller rotational speed, rpm
N_{js}	Just suspended speed, rpm
P	Power draw or power consumption, W
P_o	Power draw or power consumption without solid particles, W
S	Zwietering correlation constant
T	Internal tank diameter, m
ϑ	Kinematic viscosity, m ² /s
ρ_l	liquid density (kg/m ³)
ρ_s	solid density (kg/m ³)
X	Zwietering's mass ratio percent (mass of

The original equation proposed by Zwietering to predict N_{js} (Eq. 1) correlates the difference in the density of the solid and liquid, kinematic viscosity of the liquid, particle diameter, volume concentration of the particles, diameter of the stirring impeller and off-bottom clearance of the impeller (Zwietering, 1958).

Nienow (1968) later proposed that suspension speed was also a function of impeller clearance. He presented the effect of impeller clearance on fluid flow pattern and particle distribution. Other researchers have further extended this correlation to consider solid concentration (Ayranci & Kresta, 2014) and porous particles (Ibrahim, Jasnin, Wong, & Baker, 2012). Another approach based on the sedimentation-dispersion model has also been used to describe particle concentration profiles using modified Peclet number (Yamazaki, Tojo, & Miyanami, 1986). They proposed an equation for N_{js} by correlating the difference in the density of the solid and liquid, kinematic viscosity of the liquid, particle diameter, volume concentration of particles, diameter of the stirring impeller and off-bottom clearance of the impeller. Many researchers and investigators have proposed similar correlation equations (Baldi, Conti, & Alaria, 1978; Bohnet & Niesmak, 1979; Nienow, 1968). Kasat & Pandit (2008) specifically reviewed solid-liquid-gas dispersion systems and solid-liquid systems, including N_{js} . Baldi et al. (1978) presented a theoretical background for the correlation equation proposed by Zwietering (Zwietering, 1958). N. Sharma & A. Shaikh (2003) conducted extensive suspension experiments with the tank diameter in the range of 15–121cm and the impeller/tank diameter ratio (D/T) from 0.083 to 0.625, using spherical glass beads of four different sizes and pitched blade turbines with four and six blades as the impellers in order to develop a universal correlation for the critical speed of suspension, N_c .

Various approaches have been proposed to characterise and pinpoint N_{js} experimentally. Table 1 summarises the selected methods with the associated comments on the criteria used for characterizing N_{js} . Jafari, Chaouki, & Tanguy (2012) performed a comprehensive review on the methods for determining

N_{js} and commented on the difficulty of implementation and accuracy of the results using a scale of 1 – 5 for both criteria. However, a clear description on the scale was not provided.

In this work, the approach proposed by Rewatkar, Rao, & Joshi (1991) was further explored and a simplified mathematical model was proposed to predict N_{js} by analysing the impeller power consumption during the particle suspension process.

2. Methods and Materials

Experiments were conducted in a transparent, flat-bottomed, top-open cylindrical Perspex tank with an internal diameter (T) of 400mm. The tank was fixed with four identical baffles, which were equally spaced with a width of T/10. The liquid height to tank diameter ratio (H/T) was fixed as 1. Glass beads (Ballotini) with a particle size distribution of 550–700 μ m and bulk density of 2,500kg/m³ were used as the solid phase. Distilled water was used as the liquid phase. Solid loadings were varied within the range of 0–27 wt% (0, 5, 9, 13, 17, 21, 24 and 27 wt. %). Agitation was achieved by a standard Rushton turbine with a diameter of D=T/3 (133mm). The off-bottom clearance was set at D for all experiments. The impeller speed was measured by a portable tachometer (Lutron Electronic, Taiwan) and the power consumption was determined by the shaft torque method described in our previous work (Afshar Ghotli, Abdul Aziz, Ibrahim, Baroutian, & Arami-Niya, 2013) in which an extension shaft attached on the motor passes the rotational force to a load cell. The signal from the load cell was pre-calibrated and the power consumption, P was calculated using Eq. 2.

$$P = 2\pi N\tau \quad (2)$$

where the torque force, $\tau = mgd_L$.

3. Results and Discussion

3.1 Power number

A reliable mixing system that is comparable with other stirred vessels was developed to complete the experiment. The system was equipped with a Rushton turbine and it exhibited a power number of 5.3 which was comparable to the values reported by Beshay, Kratěna, Fořt, & Brůha (2001) (5.425) and Rutherford, Mahmoudi, Lee, & Yianneskis (1996) (5.3) for a small system (it was T=300mm in this work) as illustrated in Figure 1. The power number is also in good agreement with the values calculated by Eq. 3 (Bujalski, Nienow, Chatwin, & Cooke, 1987).

$$N_p = 2.512 \left(\frac{t}{D}\right)^{-0.195} \left(\frac{T}{T_0}\right)^{0.063} \quad (3)$$

3.2 Model development

Cubic equation was used to model the net power consumption required to suspend solids from the bottom of the tank. Figure 2 illustrates the three main stages that could be identified with increase of impeller speed, marked as initial stage, before and after just suspended condition, respectively. During the initial stage, solids remained on the bottom or just started to suspend at low

impeller speed. As the impeller speed increased, more solid particles got suspended, as illustrated in Figure 2 (a).

Figure 1: Relationship between power number and Reynolds number.

The bulk density of the fluid (or slurry) increased as more solids got suspended and the power required to maintain the impeller speed increased until the system reached the just suspended condition. At the just suspended condition and just suspended speed, N_{js} , all solid particles were suspended from the tank bottom. There was no more increment in the fluid bulk density beyond this stage, as illustrated in Figure 2 (c). Contrary to the previous trend, the fluid bulk density near the impeller and tank bottom started to reduce as solid particles got dispersed throughout the tank. This indicated that the gradient of net power consumption to increase the impeller speed would reduce beyond N_{js} . This phenomenon caused a deflection of gradient when the impeller speed reached N_{js} . Figure 2 shows that the deflection point and the net power consumption trends were comparable to the cubic equation graphs. Figure 3 shows similar trends for different solid concentrations.

Table 1: Methods for determining just suspension speed (N_{js})

Concept / Criteria	Advantage / Disadvantage	Ref
Concept Visual observation of particles at the tank bottom. Criteria Particles do not rest on the vessel bottom for more than 2s.	Advantage <ul style="list-style-type: none"> Simple and Non-intrusive. Most widely used criteria. Disadvantage <ul style="list-style-type: none"> Not applicable when the system is opaque. High degree of error for high solid loadings. Highly dependent on user attention. 	(Zwietering, 1958)
Concept Visual observation of the slurry height. Criteria Disappearance of the slurry height.	Advantage <ul style="list-style-type: none"> Simple and Non-intrusive. Widely used for high solid loading. Disadvantage <ul style="list-style-type: none"> Not applicable for opaque systems. In systems with smaller particles, the particle rise results in vanishing interface. 	(Zhu & Wu, 2008)
Concept Analyze power consumption Criteria Analysis of power consumption when the amount of suspended solids increases (N_{js}).	Advantage <ul style="list-style-type: none"> Non-intrusive. Applicable for opaque systems. Disadvantage <ul style="list-style-type: none"> Power is difficult to measure. Criteria are not well defined in the literature. 	(Rewatkar et al., 1991)
Concept Analyze the continuity of solid concentration near the tank bottom Criteria A level of continuity of solid concentration near the tank bottom is used to characterise N_{js} .	Advantage <ul style="list-style-type: none"> Applicable for opaque systems. Disadvantage <ul style="list-style-type: none"> Intrusive. It is difficult to measure solid concentration. 	(Musil & Vlk, 1978)
Concept Change in pressure at the tank bottom. Criteria A change in the pressure at the tank bottom is defined to characterise N_{js}	Advantage <ul style="list-style-type: none"> Non-intrusive. Applicable for opaque systems. Disadvantage <ul style="list-style-type: none"> Requires recording ports at the tank bottom. Affected by dynamic pressure head. 	(Micale, Grisafi, & Brucato, 2002)
Concept Measure solid concentration using fiber optic probes Criteria Solid distribution in the tank is used to characterise N_{js}	Advantage <ul style="list-style-type: none"> Applicable for high solid loadings Disadvantage <ul style="list-style-type: none"> Require special optical equipment. Criteria are not clearly defined. 	(Jafari, Tanguy, & Chaouki, 2012)

The deflection point can be calculated using the following derivation:

Let P = the net power consumption, W
 N = the impeller speed, rpm

$$P = AN^3 + BN^2 + CN + D$$

$$\frac{dP}{dN} = 3AN^2 + 2BN + C$$

$$\frac{d^2P}{dN^2} = 6AN + 2B$$

Reflection point occurred when $\frac{d^2P}{dN^2} = 0$

Thus,

$$6AN_{JS} + 2B = 0$$

$$N_{JS} = \frac{B}{3A}$$

Where N_{JS} is the just suspended speed, A and B are the coefficients for N^3 and N^2 of the cubic equation, respectively.

Figure 2: Effect of power consumption on impeller speed at solid loading of 27%.

3.2 Model application

The predicted N_{JS} by the model showed a good approximation to the experimental values obtained using the Zwietering criteria. The model over-predicted N_{JS} values by 13% and solid concentration below 5% wt could be explained by the lack of bulk density change throughout the system as more solid particles got suspended. The predicted N_{JS} values only deviated between 2 – 10% for solid concentrations between 9 – 30% wt.

Figure 3: Effect of power consumption on impeller speed at different solid loading

Figure 3 shows similar increment trend of net power consumption when the impeller speed increased at

different solid loadings. The suspension processes to achieve just suspended condition and ultimate solid suspension stage were similar, as illustrated in Figure 2. However, this method was applicable for a limited range of solid concentration and resolution of power measurement. Figure 4 shows that the predicted N_{js} values were in good approximation with the experimental N_{js} data.

Figure 4: Comparison of N_{js} predicted data and experimental data using cubic regression

This method is non-dependent on the judgment of the observer as in the Zwietering observation method and can be further extended to opaque systems. The method is highly recommended for industrial processes, as errors for larger systems due to power measurement resolution will be reduced.

4. Conclusion

A simplified mathematical model was developed to predict N_{js} by analysing the net impeller power consumption to suspend solid particles. The predicted N_{js} values showed a good approximation to the experimental values obtained using the Zwietering criterion with a deviation of 2 – 10%. The deviations decreased for higher solid concentrations.

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