FLOTATION '25
November 17-20, 2025 | Cape Town, South Africa

The effect of design and operational parameters on coarse particle suspension in a conventional flotation cell

German Lastra[1], Juan Jose Frausto[1], Bellson Awatey[1], David Deglon[2], Kym Runge[1]

[1]*Julius Kruttschnitt Mineral Research Centre, The University of Queensland, Australia*

[2]*Centre for Minerals Research, University of Cape Town, South Africa*

Abstract

As ore grades decline, the minerals industry faces increasing pressure to reduce energy use. Flotation of coarse particles presents an opportunity to reduce grinding intensity. However, mechanical flotation cells typically exhibit poor recovery of coarse material. A critical challenge is maintaining particle suspension without inducing excessive turbulence, which promotes detachment from bubbles. Optimal coarse particle flotation likely occurs at the just suspension impeller speed (Njs), where complete off-bottom suspension is achieved with minimal turbulence.

This study investigates coarse particle suspension in a 1 m³ mechanical flotation cell equipped with interchangeable features, focusing on the effect of key design and operational parameters—impeller size, off-bottom clearance, baffling and superficial gas velocity (Jg)—on Njs. Experimental design and statistical regression modelling were employed to evaluate the significance of factors. All variables were found to have a significant effect on Njs, with results showing that suspension behaviour is governed by complex interactions. The optimal configuration for coarse particle suspension was achieved using a large impeller with baffles, operated at low clearance and low air rate. These findings provide practical guidance for improving flotation performance, particularly coarse particle recovery.

1. Background

In the minerals industry, ore grades are declining across most commodities (Giurco et al., 2010; Calvo et al., 2016). As a result, hard rocks must undergo more intensive grinding to achieve the particle size and liberation required for processing in conventional flotation cells. Grinding is a high energy-intensive process (Radziszewski, 2002; Ballantyne & Powell, 2014; Napier-Munn, 2015; Jeswiet & Szekeres, 2016; Lastra et al., 2021). Therefore, reducing grinding intensity by recovering mineral particles at coarser size ranges can yield substantial energy savings, while also improving dewatering and water recovery (Ballantyne et al., 2012; Ata & Jameson, 2013; Deniz, 2013; Fosu et al., 2015; Allen, 2021).

*Corresponding author: German Lastra (g.lastra@uq.edu.au)

Mechanical flotation cells remain the industry standard for separation (Wills & Finch, 2016). They are designed and operated to maximize recovery of intermediate-size particles (10-150 μm), but perform poorly for fines and coarse particles (Gaudin et al., 1942; Trahar, 1976; Subrahmanyam & Forssberg, 1988; Falutsu & Dobby, 1989; Ata & Jameson, 2013; Kohmuench et al., 2018). Flotation of coarse particles presents particular challenges. Coarse particles tend to settle readily due to their mass, making suspension difficult. Complete suspension is essential to maximize the surface exposure of mineral particles for interaction with bubbles (Schubert et al., 1982; Kasat & Pandit, 2005; Zheng et al., 2005a; Lima et al., 2009; Ayranci et al., 2012). However, achieving this requires elevated turbulence, which increases the disruptive forces that promote particle–bubble detachment. Coarse particles are subjected to stronger detachment forces due to their physical properties (Morris, 1950; Schulze, 1977; Rodrigues et al., 2001; Nguyen & Schulze, 2003; Fosu et al., 2015).

Consequently, the optimal hydrodynamic environment for coarse particle flotation likely occurs at the critical impeller speed, or just suspension speed (Njs), the minimum impeller speed at which no solids remain stationary on the bottom. Operating at the Njs minimizes turbulence while ensuring complete off-bottom suspension, potentially maximizing coarse particle recovery (Schulze, 1984; Hui & Ahmed, 1998; Deglon, 2005; Xu, 2011; Newcombe et al., 2012; Awatey, 2015).

2. Previous research studying Njs

Despite its importance, few studies have examined the parameters influencing Njs in mechanical flotation cells. Van der Westhuizen & Deglon (2007) investigated suspension in a 125 L Batequip cell, concluding that the critical impeller speed is an appropriate measure of the effectiveness of solids suspension in a mechanical flotation cell. Subsequent work found that particle size and air rate have strong effects on Njs (Van der Westhuizen & Deglon, 2008). Lima et al. (2009) reported similar findings using 6 L Denver and Wemco flotation cells. These studies focused solely on particle properties and operating variables, leaving the influence of design parameters on Njs unexplored in mechanical flotation cells. In contrast, extensive research in mixing tanks has shown that design factors significantly affect Njs (Zwietering, 1958; Conti et al., 1981; Chudacek, 1985; Gray, 1987; Myers & Fasano, 1992; Oldshue & Sharma, 1992; Wu et al., 2001; Myers et al., 2013). Impeller size, off-bottom clearance, and baffling arrangements have been identified as critical parameters (Nagata, 1975; Raghava Rao et al., 1988; Rewatkar et al., 1991; Myers & Fasano, 1992; Dutta & Pangarkar, 1995;

Armenante & Nagamine, 1998; Sharma & Shaikh, 2003; Spidla et al., 2005; Wang et al., 2012; Devarajulu & Loganathan, 2016).

Mesa (2020) compared mixing tanks with conventional flotation cells and found that their hydrodynamics differ, indicating that findings in mixing tanks may not apply directly to mechanical flotation cells. The work also showed that a stator reduces fluid velocities, suggesting that rotor–stator systems may be suboptimal for suspension and highlighting the need to explore alternative design configurations.

The present study investigates the impact of design and operational parameters—impeller size, off-bottom clearance, baffling and air rate—on coarse particle suspension by measuring the critical impeller speed (Njs) in a 1 m^3 conventional flotation cell.

3. Experimental

The testwork was performed in a 1 m^3 mechanical flotation rig with a transparent tank of 1.15 m diameter (Figure 1). The cell operated in batch mode with silica added to water in the tank prior to commencement of the experiments. The cell was not fitted with a feed or tailing line as these would have resulted in disruption to the hydrodynamic flow patterns. The static liquid level was 0.57 m. A 11 kW three-phase electric motor powered a 6-blade Metso RCS rotor mechanism through a variable speed drive and V-belt assembly. Impeller speed was measured with a digital tachometer. Air was supplied by a blower and regulated with a manual valve. A digital sensor measured airflow rate. Water was used as the liquid phase, with 100 ppm of methyl isobutyl carbinol (MIBC) added to stabilize bubble size.

Figure 1. Pilot flotation rig.

A camera positioned beneath the cell and connected to a monitor enabled observation of particle settling on the bottom. A total of 1 kg of +106-150 µm silica was used as the suspension tracer. The cell was operated at low percent solids, with the tracer being the only solid material present to facilitate assessment of suspension behaviour. Suspension was assessed by gradually increasing impeller speed until solids did not settle for more than one second (Zwietering, 1958). This speed was recorded as the critical impeller speed (Njs).

The study was conducted using a full factorial design comprising 48 experiments, with an additional 8 repeats to estimate experimental error. Table 1 outlines the tested factors and levels. Two impeller sizes were employed (0.205 m and 0.247 m diameter), with interchangeable stator and baffles configurations. Baffles and stator were tested separately. Impeller off-bottom clearance was adjusted by changing the position of the frame supporting the tank. The cell was specially designed so that the mechanism was mounted independently from the tank, allowing the clearance between the impeller and the cell base to be varied.

Table 1. Experimental design.

Factor	Levels
Impeller size (m)	0.205, 0.247
Baffling	Stator, Baffles
Clearance (m)	0.05, 0.10, 0.15
Jg (cm/s)	0.0, 0.5, 1.0, 1.5

4. Results and discussion

The experimental results were analyzed using statistical regression modelling to evaluate the significance of the studied variables on the critical impeller speed (Njs). The Means of Means method was employed to explore trends and their underlying causes.

4.1. Statistical regression modelling

A regression model was developed to identify significant variables and interactions:

$$\begin{aligned}\text{Njs [RPM]} = {} & 800 - 2492\ \text{Impeller Size [m]} + 8606\ \text{Clearance [m]} + 1315\ \text{Jg [cm/s]} - 675\ \text{Baffling} \\ & - 150.5\ \text{Jg [cm/s]} * \text{Jg [cm/s]} - 31044\ \text{Impeller Size [m]} * \text{Clearance [m]} \\ & - 3942\ \text{Impeller Size [m]} * \text{Jg [cm/s]} + 2750\ \text{Impeller Size [m]} * \text{Baffling} \\ & + 823\ \text{Clearance [m]} * \text{Jg [cm/s]} - 970\ \text{Clearance [m]} * \text{Baffling} - 90.1\ \text{Jg [cm/s]} \\ & * \text{Baffling}\end{aligned}$$

The model has an R^2 of 97.1% (Table 2), indicating excellent predictive capability.

Table 2. Metrics of the regression model.

Indicator	Value
R^2 (%)	97.1
R^2 adjusted (%)	96.3
Standard Error (RPM)	47.5
Observations	56

Table 3 presents the p-value of the model terms. Terms with $p<0.05$ (95% confidence) were considered statistically significant.

Table 3. P-values of the model terms.

Term	P-Value
Constant	0.001
Impeller Size [m]	0.014
Clearance [m]	0.000
Jg [cm/s]	0.000
Baffling	0.000
Jg [cm/s]*Jg [cm/s]	0.000
Impeller Size [m]*Clearance [m]	0.000
Impeller Size [m]*Jg [cm/s]	0.000
Impeller Size [m]*Baffling	0.000
Clearance [m]*Jg [cm/s]	0.007
Clearance [m]*Baffling	0.004
Jg [cm/s]*Baffling	0.000

4.2. Main effects

All studied variables—impeller size, clearance, Jg and baffling—had a significant overall impact on the critical impeller speed (Figure 2).

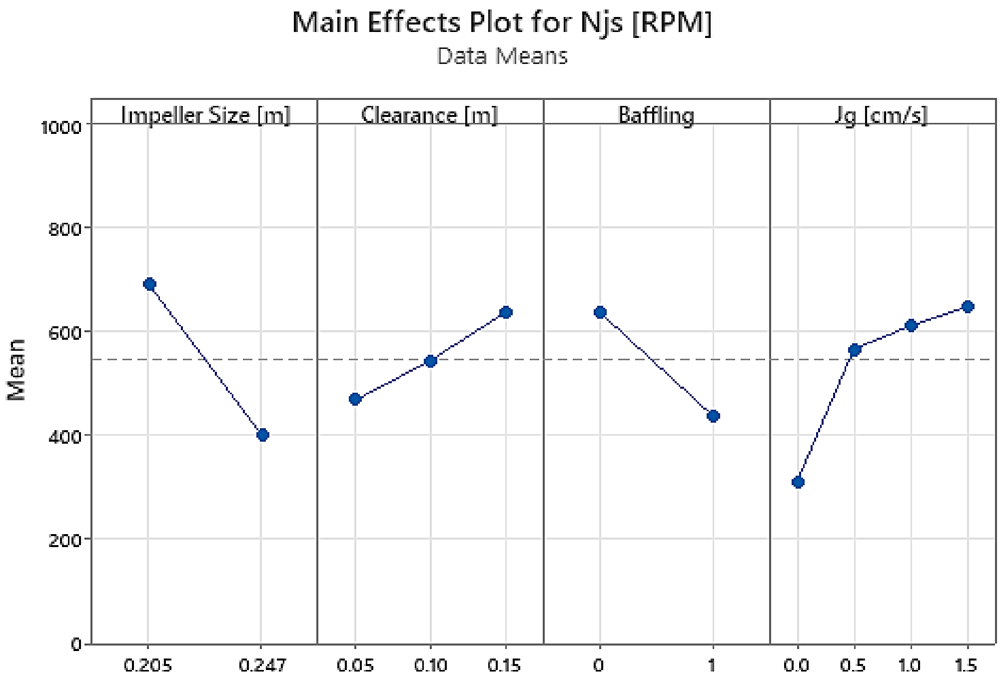

Figure 2. Main effects of impeller size, clearance, baffling (0:Stator only, 1:Baffles only) and Jg on the critical impeller speed.

4.2.1. Impeller size

Coarse particle suspension was influenced by impeller size, with the large impeller significantly reducing Njs. Several studies in mixing tanks have reported similar trends under various conditions (Rewatkar et al., 1991; Nienow, 1997; Armenante & Nagamine, 1998; Sharma & Shaikh, 2003; Kasat & Pandit, 2005). Suspension occurs due to fluid flow and turbulence (Ayranci et al., 2012). According to Raghava Rao et al. (1988), a larger impeller diameter reduces the flow path to reach the solids sitting on the base of the cell, minimizing turbulence decay and enhancing suspension. Mesa (2020) observed that impellers with larger blades generate faster flows. A larger rotor has bigger blades, which explains why Gao et al. (2021) found that increasing rotor diameter leads to higher flow velocities. These findings are consistent with the larger blade area transferring mechanical energy to a greater fluid volume. Consequently, more fluid is pumped, generating higher velocities that promote complete suspension at lower critical impeller speed.

4.2.2. Impeller off-bottom clearance

Impeller off-bottom clearance had a noticeable effect on coarse particle suspension. Lower clearance was found to reduce Njs. Previous studies have shown that clearance influences the impeller suspension capacity (Zwietering, 1958; Mavros, 1992; Ibrahim & Nienow, 1996;

Armenante & Nagamine, 1998). Nienow (1968) and Chapman et al. (1983a) observed that decreasing clearance lowers Njs for radial turbines. At lower clearance, the impeller is closer to the solids sitting on the base of the cell, shortening the flow path length. This minimizes turbulence decay and increases liquid velocity (Raghava Rao et al., 1988). Consequently, more energy is imparted to the solids, which enhances suspension and enables complete off-bottom suspension at lower Njs.

4.2.3. Baffling

Baffling also had a significant effect on coarse particle suspension. Replacing the stator with baffles reduced the critical impeller speed. According to Fallenius (1987), a stator converts a substantial portion of mean flow energy into turbulence. Particle suspension is more effective when mean flow dominates (Nagata, 1975; Nguyen & Schulze, 2003; Paul et al., 2004). Therefore, the rotor-stator combination may be suboptimal for suspension. Mesa (2020) observed that the stator affects cell hydrodynamics extensively, while baffles mostly influence local fluid velocities and promote turbulence in smaller regions. By converting less mean flow into turbulence, baffles enhance suspension and lower Njs compared to a stator.

4.2.4. Superficial gas velocity

Superficial gas velocity (Jg) played an important role in coarse particle suspension. Numerous studies have confirmed that gas injection affects solids suspension (Zlokarnik & Judat, 1969; Jameson, 1984; Mavros, 1992; Van der Westhuizen, 2004; Zheng et al., 2005b; Van der Westhuizen & Deglon, 2008; Lima et al., 2009; Jafari et al., 2012; Jaszczur & Młynarczykowska, 2020). This behaviour can be attributed to several mechanisms:

- Rotating impellers create high velocity, low pressure vortices behind the blades. These regions attract air, forming cavities that raise local pressure and reduce drag, lowering power draw (Arbiter et al., 1969; Warmoeskerken et al., 1984; Rewatkar et al., 1991).
- Air occupies part of the impeller blade area, displacing slurry that would otherwise receive mechanical energy. Together with the reduced effective fluid density, this results in a detrimental effect on impeller pumping capacity and fluid circulation velocity (Nienow, 1997; Nelson et al., 2009). Brayant & Sadeghzadeh (1979) and Joshi et al. (1982) reported that liquid velocities in radial turbine-agitated vessels decrease with increasing gas rate.
- Air dampens local turbulence, reducing energy dissipation in the system (Chapman et al., 1983b).

- Air lowers liquid-solid slip velocity, which decreases the interphase forces (drag and lift) responsible for suspending particles from the vessel base (Jafari et al., 2012).

These combined effects deteriorate solids suspension. Consequently, higher Jg resulted in increased Njs. This impact was non-linear: initial air injection substantially raised Njs, while subsequent increases in Jg produced smaller increments in Njs as the detrimental effects became less pronounced. This trend aligns with the findings of Rewatkar et al. (1991). They observed that for a radial turbine, Njs gradually increases with Jg, but the rate of increase diminishes at higher gas velocities.

4.3. Interactions

The regression results indicate that all interactions are significant, highlighting that interactive effects are crucial for understanding the impact of design and operational parameters on Njs.

4.3.1. The impeller size-clearance interaction

Figure 3 shows the interaction between impeller size and clearance on Njs. With the standard rotor, increasing clearance substantially raises the critical impeller speed. The larger rotor can suspend particles more effectively (Raghava Rao et al., 1988; Rewatkar et al., 1991). Therefore, the increase in Njs due to higher clearance is less pronounced. Similar findings were reported by Armenante & Nagamine (1998) for disc and flat-blade turbines.

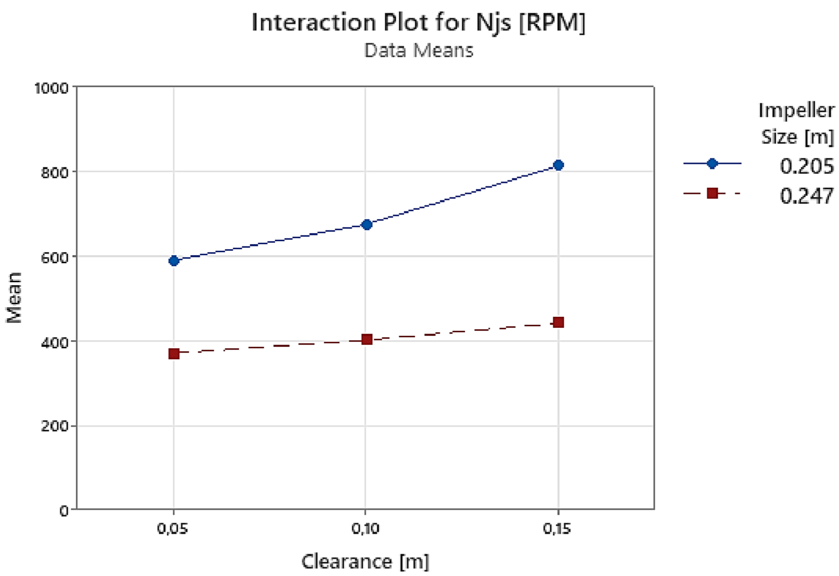

Figure 3. Effect of clearance on Njs at two rotor sizes.

Other studies in mixing tanks have also reported interactions between impeller size and clearance (Nienow, 1997; Jaworski et al., 2001). For a radial impeller, increasing the diameter reduces turbulence decay by shortening the flow path, and enhances liquid velocities. Raghava Rao et al. (1988) proposed that the change in path length due to a change in impeller diameter becomes increasingly more pronounced with a reduction in clearance. As a result, the effect of diameter on Njs is stronger as clearance decreases. However, impeller suspension capacity depends not only on flow path length but also on the ability to transfer mechanical energy to the fluid and solids. A larger impeller reduces path length, but also increases fluid velocity and turbulence by transferring energy to a larger volume of fluid, a factor not considered by Raghava Rao et al. (1988) in their analysis of the impeller size-clearance interaction.

Furthermore, Raghava Rao et al. (1988) referred to radial turbines, which have smaller blades than rotors. Mesa (2020) found that smaller blades generate slower fluid velocities. Consequently, for turbines, the effect of increasing size may be dominated by the reduced path length. In contrast, for rotors, the effect of size could be dominated by increased fluid velocities because of the larger blades. Therefore, at lower clearance, the faster flows produced by a rotor facilitate suspension, making the impact of reduced path length less critical and the overall effect of rotor size less pronounced.

4.3.2. The impeller size-Jg interaction

Figure 4 illustrates how Njs responds to changes in Jg for two rotor sizes. For the standard impeller, higher Jg leads to a pronounced increase in the critical impeller speed. Chapman et al. (1983c) reported that under gassed conditions, larger impellers operate more stably, experiencing less power fluctuations than smaller ones. According to Nienow et al. (1985), this makes larger impellers better suited for handling suspension at high gassing rates. This is consistent with larger impellers having bigger blades, which transfer mechanical energy to a greater volume of fluid, including air. Consequently, more fluid can be pumped, and the suspension efficiency is less affected when air occupies part of the pumped volume, resulting in smaller increase in Njs with higher Jg.

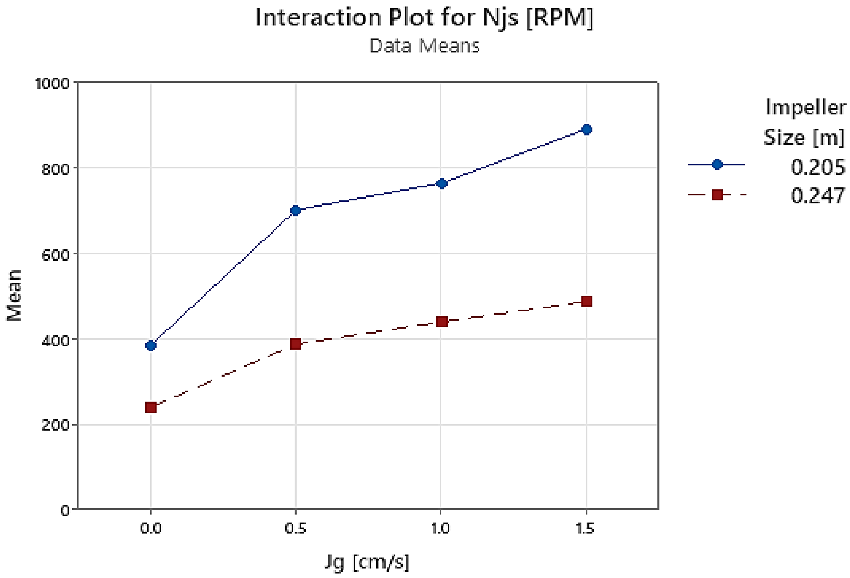

Figure 4. Impact of Jg on Njs at two rotor sizes.

4.3.3. The impeller size-baffling interaction

Figure 5 shows the interaction between impeller size and baffling. Operating with a stator results in poorer suspension and higher Njs compared to baffles. The standard rotor has limited particle suspension capacity and is therefore strongly affected by the reduction in suspension caused by the stator, resulting in a more pronounced increase in Njs. In contrast, the large rotor suspends solids more effectively, making its performance less sensitive to changes in baffling arrangement. Consequently, the impact of baffling on Njs is smaller for the large rotor.

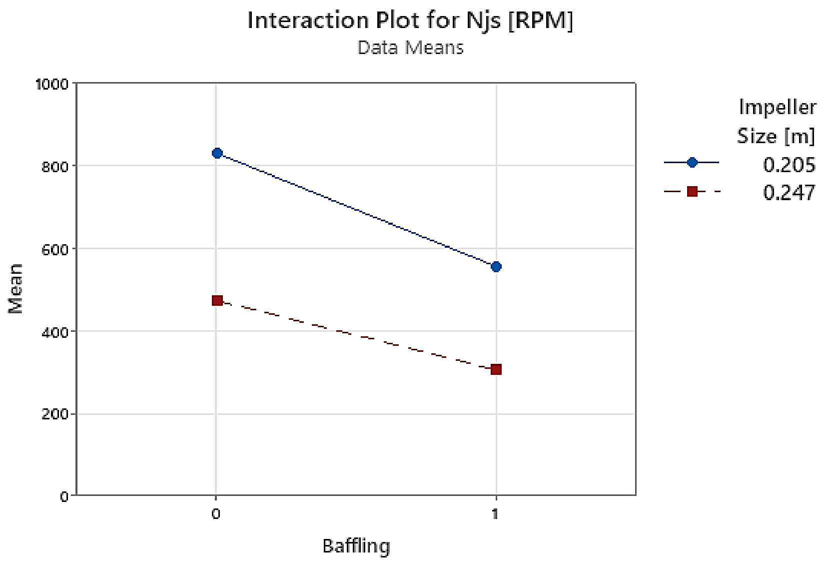

Figure 5. Effect of baffling on Njs at two rotor sizes.

4.3.4. The clearance-Jg interaction

The regression model shows a significant interactive effect of Jg and clearance on Njs. Air injection deteriorates solids suspension, causing higher Jg to increase the critical impeller speed (Van der Westhuizen, 2004; Van der Westhuizen & Deglon, 2008). Figure 6 illustrates how this effect varies with clearance. At low clearance, the impeller is close to the particles at the bottom, allowing effective suspension and making its performance less sensitive to airflow. Consequently, the effect of Jg on Njs is small. At higher clearance, the rotor is far from the bottom, affecting its ability to transfer mechanical energy to the solids. As a result, suspension becomes more sensitive to air injection, leading to a greater increase in Njs with higher Jg.

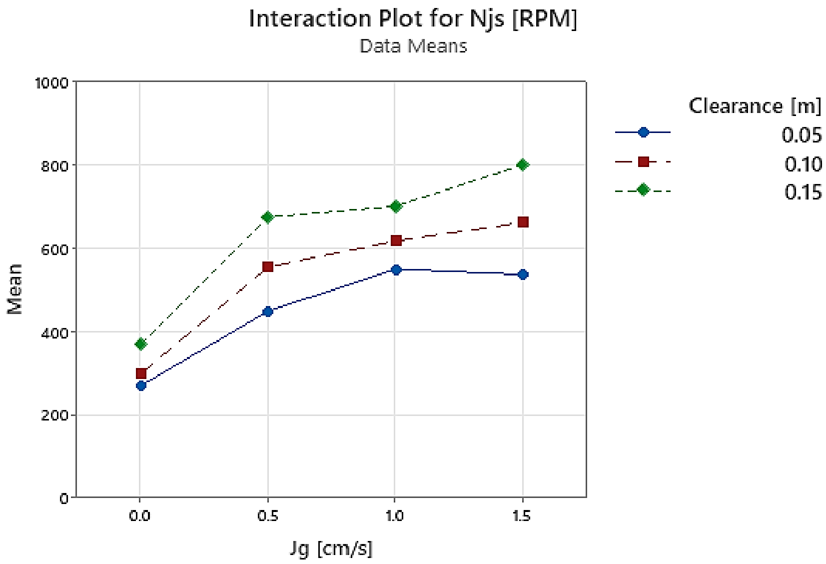

Figure 6. Impact of Jg on Njs at three clearances.

4.3.5. The baffling-clearance interaction

Figure 7 presents the impact of clearance on Njs for the stator and baffles. The stator generates hydrodynamic conditions (more turbulence and less mean flow) that are detrimental for suspension. Consequently, the rotor struggles more to suspend particles with the stator, making its suspension capacity more sensitive to the adverse effects of increasing clearance, which leads to a marked rise in Njs. With baffles, the impeller can achieve complete off-bottom suspension more readily. Therefore, increasing clearance has a smaller impact on suspension capacity and results in a less pronounced increase in Njs.

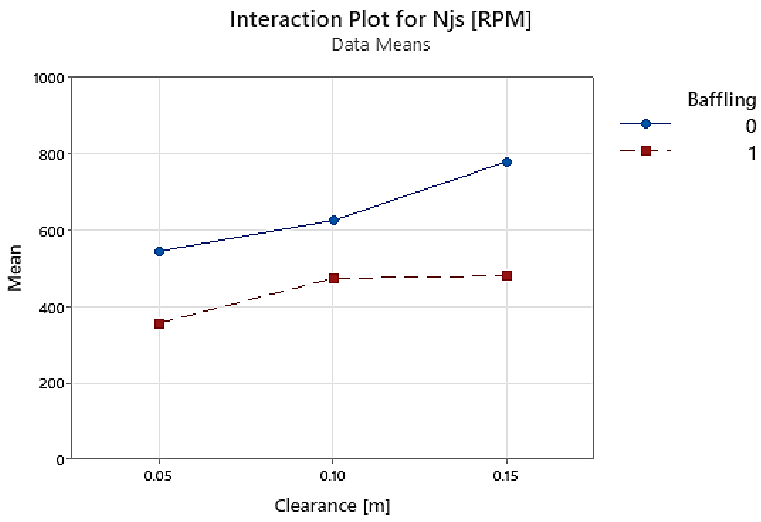

Figure 7. Effect of clearance on Njs for stator and baffles arrangements.

4.3.6. The baffling-Jg interaction

Figure 8 shows a minor but statistically significant interaction between baffling and Jg. Higher airflow reduces particle suspension, increasing Njs. However, this effect depends on the baffling arrangement and Jg level. At low Jg (e.g., 0.0 to 0.5 cm/s), Njs increases more for the stator than for baffles because the stator makes particles harder to suspend, so the impeller suspension performance is more sensitive to air injection. At higher Jg (e.g., 0.5 to 1.5 cm/s), the increase in Njs is more pronounced for baffles than for the stator. This may be because the stator can break bubbles more effectively, mitigating the detrimental impact of additional air on suspension, while baffles are less effective at bubble breakage, which becomes increasingly important as airflow rises.

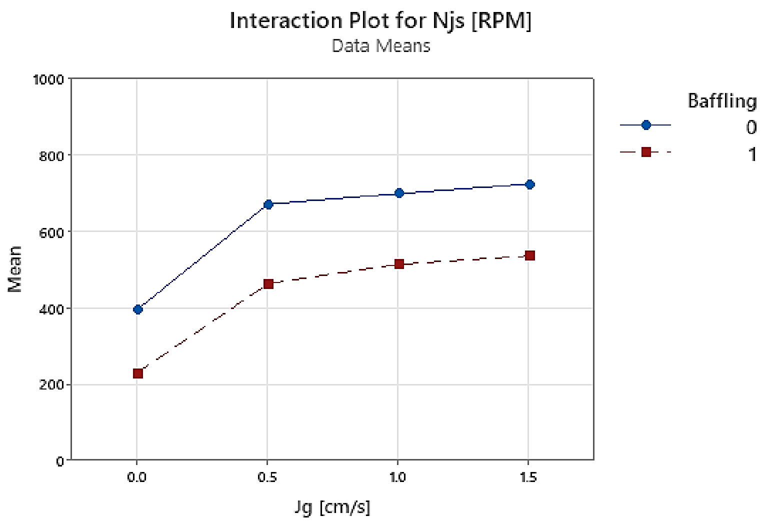

Figure 8. Impact of Jg on Njs for stator and baffles arrangements.

5. Implications for coarse particle flotation

A conventional flotation cell typically operates with a standard rotor-stator mechanism at a standard clearance and moderate air rate. The results, although at very low solid concentrations, demonstrated that such a configuration is sub-optimal for coarse particle suspension. Increasing the impeller size, replacing the stator with baffles, and reducing both clearance and air rate resulted in a lower critical impeller speed (Njs). Therefore, the optimal configuration for coarse particle suspension is a large rotor with baffles, operated at low clearance and low airflow rate.

This configuration is not commonly employed in a conventional flotation cell. Although larger impellers have been used previously, they are typically operated at the same tip speed as standard impellers. In cases where impeller speed was reduced, it was not due to the impeller superior suspension capability, nor was Njs measured (Gorain et al., 1995a; Tabosa, 2012).

The clearance is difficult to modify so cells are built according to a standard that does not change for different applications (Gorain et al., 1995b, 1995c). Air rate is often varied, but usually at a fixed impeller speed (Laplante et al., 1983a, 1983b; Ostadrahimi et al., 2021). This does not take advantage of the potential to reduce impeller speed at lower air rates.

The use of baffles in flotation is very novel. Only one study has investigated the effect of replacing the stator with baffles, but they focused on hydrodynamics at a fixed impeller speed (Mesa, 2020).

The improved configuration modifies the cell hydrodynamics and enables operation at a lower Njs, which can significantly benefit coarse particle flotation. Lower impeller speed typically leads to reduced turbulence and power input, decreasing bubble-particle detachment. Replacing the stator with baffles can have a similar effect by enhancing mean flow over turbulence.

The modifications may also influence bubble size. In addition, lower Njs could reduce turbulence at the pulp-froth interface, decreasing drop-back and improving froth recovery. Power draw, bubble size and interface oscillations were measured during the experiments and will be presented in a future publication.

The experiments in this study were conducted in batch mode at low percent solids. Results may differ under real plant conditions, where higher solids concentrations and continuous operation can influence suspension behaviour. Under steady-state conditions, for a cell operating continuously, a false bottom of particles may form beneath the impeller, and the feed and tailings flows can modify cell hydrodynamics. Ultimately, the extent to which these modifications improve coarse particle recovery will need testing on site in a continuous flotation cell at a solids concentration typical of real plant operation. This will be the focus of future test work.

6. Conclusions

This study employed a 1 m^3 conventional flotation cell to investigate the effects of design and operational parameters on coarse particle suspension, quantified by the critical impeller speed for complete off-bottom suspension (Njs). A statistical regression model was developed to evaluate the significance of the studied variables. Results showed that Njs is influenced by impeller size, off-bottom clearance, baffling and superficial gas velocity (Jg). All interactions were found to be significant, highlighting that solids suspension in mechanical flotation cells is a complex phenomenon governed by interactive effects. This work demonstrated that coarse particle suspension can be optimized using a large rotor with baffles, operated at low clearance and low airflow rate. These findings deepen the understanding of how cell design and operating conditions affect suspension dynamics and provide practical guidance for improving flotation performance, particularly coarse particle recovery.

7. Acknowledgements

The authors acknowledge the sponsors of the Collaborative Consortium for Coarse Particle Processing Research (Aeris Resources, Anglo American, Eriez Flotation Division, Glencore Copper, Hudbay, Newmont and Rio Tinto) and the University of Queensland for the financial support to conduct this research. Funding was also provided by the Australian Research Council for the ARC Centre of Excellence for Enabling Eco-Efficient Beneficiation of Minerals, grant number CE200100009. Participation in this conference was made possible through funding from the SMI Bill Whiten Memorial Award.

The authors also express their gratitude to Tailing Technology, a flotation equipment supplier based in South Africa, who generously designed the 1 m^3 flotation cell, and built and shipped a standard and an oversized RCS mechanism with their associated stators to the SMI-JKMRC for incorporation into the test cell. The authors also greatly thank Michael Kilmartin for manufacturing the flotation rig and assisting in its commissioning, and Mitchell Alexander for his support in implementing design modifications throughout the experimental program. Special thanks to Emeritus Professor Tim Napier-Munn for his valuable assistance with experimental design and statistical regression modelling.

8. References

Allen, M. (2021). *A high-level study into mining energy use for the key mineral commodities of the future*. Engeco.

Arbiter, N., Harris, C., & Yap, R. (1969). Hydrodynamics of flotation cells. *SME Transactions, 244*, 134-148.

Armenante, P., & Nagamine, E. (1998). Effect of low off-bottom impeller clearance on the minimum agitation speed for complete suspension of solids in stirred tanks. *Chemical Engineering Science, 53*(9), 1757-1775. https://doi.org/10.1016/S0009-2509(98)00001-3

Ata, S., & Jameson, G. (2013). Recovery of coarse particles in the froth phase - A case study. *Minerals Engineering, 45*, 121-127. https://doi.org/10.1016/j.mineng.2013.02.006

Awatey, B. (2015). *Fluidised-bed flotation of coarse sulphide minerals: factors influencing value recovery.* PhD Thesis. University of South Australia, Adelaide, Australia.

Ayranci, I., Machado, M., Madej, A., Derksen, J., Nobes, D., & Kresta, S. (2012). Effect of Geometry on the Mechanisms for Off Bottom Solids Suspension in a Stirred Tank. *Chemical Engineering Science, 79*, 163-176. https://doi.org/10.1016/j.ces.2012.05.028

Ballantyne, G., & Powell, M. (2014). Benchmarking comminution energy consumption for the processing of copper and gold ores. *Minerals Engineering, 65*, 109-114. https://doi.org/10.1016/j.mineng.2014.05.017

Ballantyne, G., Powell, M., & Tiang, M. (2012). *Proportion of energy attributable to comminution.* 11th AusIMM Mill Operators' Conference 2012. Hobart, Australia.

Brayant, J., & Sadeghzadeh, S. (1979). *Circulation Rates in Stirred and Aerated Tanks.* 3rd European Conference on Mixing. York, England.

Calvo, G., Mudd, G., Valero, A., & Valero, A. (2016). Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality?. *Resources, 5*(4), 36. https://doi.org/10.3390/resources5040036

Chapman, C., Nienow, A., Cooke, M., & Middleton, J. (1983a). Particle-gas-liquid mixing in stirred vessels. Part I: Particle-liquid mixing. *Chemical Engineering Research & Design, 61*, 71–81.

Chapman, C., Nienow, A., Cooke, M., & Middleton, J. (1983b). Particle-gas-liquid mixing in stirred vessels. Part III: Three phase mixing. *Chemical Engineering Research and Design, 61*(3), 167-181.

Chapman, C., Nienow, A., Cooke, M., & Middleton, J. (1983c). Particle-Gas-Liquid Mixing in Stirred Vessels: Part II Gas-Liquid Mixing. *Chemical Engineering Research & Design, 61*, 82-95.

Chudacek, M. (1985). Solids suspension behaviour in profiled bottom and flat bottom mixing tanks. *Chemical Engineering Science, 40*(3), 385-392. https://doi.org/10.1016/0009-2509(85)85100-9

Conti, R., Sicardi, S., & Specchia, V. (1981). Effect of the stirrer clearance on particle suspension in agitated vessels. *The Chemical Engineering Journal, 22*(3), 247-249. https://doi.org/10.1016/0300-9467(81)80021-4

Deglon, D. (2005). The effect of agitation on the flotation of platinum ores. *Minerals Engineering, 18*(8), 839-844. https://doi.org/10.1016/j.mineng.2005.01.024

Deniz, V. (2013). Comparisons of Dry Grinding Kinetics of Lignite, Bituminous Coal, and Petroleum Coke. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 35*(10), 913-920. https://doi.org/10.1080/15567036.2010.514591

Devarajulu, C., & Loganathan, M. (2016). Effect of Impeller Clearance and Liquid Level on Critical Impeller Speed in an Agitated Vessel using Different Axial and Radial Impellers. *Journal of Applied Fluid Mechanics, 9*(6), 2753-2761. https://doi.org/10.29252/jafm.09.06.24824

Dutta, N., & Pangarkar, V. (1995). Critical impeller speed for solid suspension in multi-impeller three phase agitated contactors. *The Canadian Journal of Chemical Engineering, 73*(3), 273-283. https://doi.org/10.1002/cjce.5450730302

Fallenius, K. (1987). Turbulence in flotation cells. *International Journal of Mineral Processing, 21*(1-2), 1-23. https://doi.org/10.1016/0301-7516(87)90002-0

Falutsu, M., & Dobby, G. (1989). Direct measurement of froth drop back and collection zone recovery in a laboratory flotation column. *Minerals Engineering, 2*(3), 377-386. https://doi.org/10.1016/0892-6875(89)90006-X

Fosu, S., Awatey, B., Skinner, W., & Zanin, M. (2015). Flotation of coarse composite particles in mechanical cell vs. the fluidised-bed separator (The HydroFloat™). *Minerals Engineering, 77*, 137-149. https://doi.org/10.1016/j.mineng.2015.03.011

Gao, S., Meng, L., Wei, D., Zhao, Q., Wang, X., & Hou, D. (2021). Influence of the Impeller Diameter and Off-Bottom Clearance on the Flow Velocity Distribution Characteristics Near the Bottom inside a Flotation Machine. *Minerals, 11*(1). https://doi.org/10.3390/min11010031

Gaudin, A., Schuhmann, R., & Schlechten, A. (1942). Flotation Kinetics. II. The Effect of Size on the Behavior of Galena Particles. *Journal of Physical Chemistry, 46*(8), 902-910. https://doi.org/10.1021/j150422a013

Giurco, D., Prior, T., Mudd, G., Mason, L., & Behrisch, J. (2010). *Peak minerals in Australia: a review of changing impacts and benefits*. University of Technology Sydney & Monash University.

Gorain, B., Franzidis, J., & Manlapig, E. (1995a). Studies on impeller type, impeller speed and air flow rate in an industrial scale flotation cell - Part 1: Effect on bubble size distribution. *Minerals Engineering, 8*(6), 615-635. https://doi.org/10.1016/0892-6875(95)00025-L

Gorain, B., Franzidis, J., & Manlapig, E. (1995b). Studies on impeller type, impeller speed and air flow rate in an industrial scale flotation cell part 2: Effect on gas holdup. *Minerals Engineering, 8*(12), 1557-1570. https://doi.org/10.1016/0892-6875(95)00118-2

Gorain, B., Franzidis, J., & Manlapig, E. (1995c). Studies on impeller type, impeller speed and air flow rate in an industrial scale flotation cell. Part 3: Effect on superficial gas velocity. *Minerals Engineering, 9*(6), 639-654. https://doi.org/10.1016/0892-6875(96)00052-0

Gray, D. (1987). Impeller clearance effect on off bottom particle suspension in agitated vessels. *Chemical Engineering Communications, 61*(1-6), 151-158. https://doi.org/10.1080/00986448708912035

Hui, S., & Ahmed, N. (1998). *The effect of vessel geometry on mixing hydrodynamics and coarse particle flotation.* 26th Australasian Chemical Engineering Conference (Chemeca 98). Port Douglas, Australia.

Ibrahim, S., & Nienow, A. (1996). Particle Suspension in the Turbulent Regime: The Effect of Impeller Type and Impeller/Vessel Configuration. *Chemical Engineering Research and Design, 74*(6), 679-688.

Jafari, R., Tanguy, P., & Chaouki, J. (2012). Characterization of Minimum Impeller Speed for Suspension of Solids in Liquid at High Solid Concentration, Using Gamma-Ray Densitometry. *International Journal of Chemical Engineering*. https://doi.org/10.1155/2012/945314

Jameson, G. (1984). Physics and Hydrodynamics of bubbles. In K. Ives (Ed.), *The Scientific Basis of Flotation* (Vol. 75, pp. 53-77). Springer. https://doi.org/10.1007/978-94-009-6926-1

Jaszczur, M., & Młynarczykowska, A. (2020). A General Review of the Current Development of Mechanically Agitated Vessels. *Processes, 8*. https://doi.org/10.3390/pr8080982

Jaworski, Z., Dyster, K., & Nienow, A. (2001). The Effect of Size, Location and Pumping Direction of Pitched Blade Turbine Impellers on Flow Patterns: LDA Measurements and CFD Predictions. *Chemical Engineering Research and Design, 79*(8), 887-894. https://doi.org/10.1205/02638760152721406

Jeswiet, J., & Szekeres, A. (2016). Energy Consumption in Mining Comminution. *Procedia CIRP, 48*, 140-145. https://doi.org/10.1016/j.procir.2016.03.250

Joshi, J., Pandit, A., & Sharma, M. (1982). Mechanically agitated gas-liquid reactors. *Chemical Engineering Science, 37*(6), 813-844. https://doi.org/10.1016/0009-2509(82)80171-1

Kasat, G., & Pandit, A. (2005). Review on Mixing Characteristics in Solid-Liquid and Solid-Liquid-Gas Reactor Vessels. *The Canadian Journal of Chemical Engineering, 83*(4), 618-643. https://doi.org/10.1002/cjce.5450830403

Kohmuench, J., Mankosab, M., Thanasekarana, H., & Hobertb, A. (2018). Improving coarse particle flotation using the HydroFloat™ (raising the trunk of the elephant curve). *Minerals Engineering, 121*, 137-145. https://doi.org/10.1016/j.mineng.2018.03.004

Laplante, A., Toguri, J., & Smith, H. (1983a). The effect of air flow rate on the kinetics of flotation. Part 1: The transfer of material from the slurry to the froth. *International Journal of Mineral Processing, 11*(3), 203-219. https://doi.org/10.1016/0301-7516(83)90026-1

Laplante, A., Toguri, J., & Smith, H. (1983b). The effect of air flow rate on the kinetics of flotation. Part 2: The transfer of material from the froth over the cell lip. *International Journal of Mineral Processing, 11*(3), 221-234. https://doi.org/10.1016/0301-7516(83)90027-3

Lastra, G., Jokovic, V., & Kanchibotla, S. (2021). Understanding the impact of geotechnical ore properties and blast design on comminution circuits using simulations. *Minerals Engineering, 170*. https://doi.org/10.1016/j.mineng.2021.107001

Lima, O., Deglon, D., & Leal Filho, L. (2009). A comparison of the critical impeller speed for solids suspension in a bench-scale and a pilot-scale mechanical flotation cell. *Minerals Engineering, 22*(13), 1147-1153. https://doi.org/10.1016/j.mineng.2009.05.002

Mavros, P. (1992). Mixing and Hydrodynamics in Flotation Cells. In P. Mavros & K. Matis (Eds.), *Innovations in Flotation Technology* (pp. 211–234). Springer, Dordrecht. https://doi.org/10.1007/978-94-011-2658-8_9

Mesa, D. (2020). *The effect of impeller-stator design on froth stability, flotation performance and flotation hydrodynamics.* PhD Thesis. Imperial College London, London, England.

Morris, T. (1950). Measurement of equilibrium forces between an air bubble and an attached solid in water. *Mining Engineering, 187*(1), 91-95.

Myers, K., & Fasano, J. (1992). The influence of baffle off-bottom clearance on the solids suspension performance of pitched-blade and high-efficiency impellers. *The Canadian Journal of Chemical Engineering, 70*(3), 596-599. https://doi.org/10.1002/cjce.5450700326

Myers, K., Janz, E., & Fasano, J. (2013). Effect of solids loading on agitator just-suspended speed. *The Chemical Engineering Journal, 91*(9), 1508-1512. https://doi.org/10.1002/cjce.21763

Nagata, S. (1975). *Mixing: Principles and applications*. Halsted Press.

Napier-Munn, T. (2015). Is progress in energy-efficient comminution doomed? *Minerals Engineering, 73*, 1-6. https://doi.org/10.1016/j.mineng.2014.06.009

Nelson, M., Lelinski, D., & Gronstrand, S. (2009). Design and operation of mechanical flotation cells. In D. Malhotra, P. Taylor, M. Lavier, & E. Spiller (Eds.), *Recent Advances in Mineral Processing Plant Design*. Society for Mining, Metallurgy, and Exploration.

Newcombe, B., Bradshaw, D., & Wightman, E. (2012). Flash flotation… and the plight of the coarse particle. *Minerals Engineering, 34*, 1-10. https://doi.org/10.1016/j.mineng.2012.03.023

Nguyen, A., & Schulze, H. (2003). *Colloidal Science of Flotation*. Taylor & Francis Group. https://doi.org/10.1201/9781482276411

Nienow, A. (1968). Suspension of solid particles in turbine agitated baffled vessels. *Chemical Engineering Science, 23*(12), 1453-1459. https://doi.org/10.1016/0009-2509(68)89055-4

Nienow, A. (1997). The suspension of solid particles. In *Mixing in the Process Industries* (2nd ed.). Elsevier Science & Technology. https://doi.org/10.1016/B978-0-7506-3760-2.X5020-3

Nienow, A., Konno, M., & Bujalski, W. (1985). *Studies on Three-Phase Mixing: A Review and Recent Results.* 5th European Conference on Mixing. Wurzburg, Germany.

Oldshue, J., & Sharma, R. (1992). The Effect of Off-Bottom Distance of an Impeller for the 'Just Suspended Speed, Njs'. *AIChE Symposium Series, 88*, 72–78.

Ostadrahimi, M., Farrokhpay, S., Gharibi, K., & Dehghani, A. (2021). Effects of Operating Parameters on the Froth and Collection Zone Recovery in Flotation: An Industrial Case Study in a 10 m3 Cell. *Minerals, 11*(5), 494. https://doi.org/10.3390/min11050494

Paul, E., Atiemo-Obeng, V., & Kresta, S. (2004). *Handbook of Industrial Mixing: Science and Practice*. John Wiley & Sons, Inc. http://doi.org/10.1002/0471451452

Radziszewski, P. (2002). Exploring total media wear. *Minerals Engineering, 15*(12), 1073-1087. https://doi.org/10.1016/S0892-6875(02)00228-5

Raghava Rao, K., Rewatkar, V., & Joshi, J. (1988). Critical impeller speed for solid suspension in mechanically agitated contactors. *AIChE Journal, 34*(8), 1332-1340. https://doi.org/10.1002/aic.690340811

Rewatkar, V., Raghava Rao, K., & Joshi, J. (1991). Critical impeller speed for solid suspension in mechanically agitated three-phase reactors. 1. Experimental part. *Industrial & Engineering Chemistry Research, 30*(8), 1770–1784. https://doi.org/10.1021/ie00056a013

Rodrigues, W., Leal Filho, L., & Masini, E. (2001). Hydrodynamic dimensionless parameters and their influence on flotation performance of coarse particles. *Minerals Engineering, 14*(9), 1047-1054. https://doi.org/10.1016/S0892-6875(01)00110-8

Schubert, H., Bischofberger, C., & Koch, P. (1982). *On the influence of hydrodynamics in flotation processes.* XIV International Mineral Processing Congress. Toronto, Canada.

Schulze, H. (1977). New theoretical and experimental investigations on stability of bubble/particle aggregates in flotation: A theory on the upper particle size of floatability. *International Journal of Mineral Processing, 4*(3), 241-259. https://doi.org/10.1016/0301-7516(77)90005-9

Schulze, H. (1984). *Physico-Chemical Elementary Processes in Flotation* (Vol. 4). Elsevier.

Sharma, R., & Shaikh, A. (2003). Solids suspension in stirred tanks with pitched blade turbines. *Chemical Engineering Science, 58*(10), 2123-2140. https://doi.org/10.1016/S0009-2509(03)00023-X

Spidla, M., Sinevic, V., & Machon, V. (2005). Effect of Baffle Design on the Off-bottom Suspension Characteristics of Axial-flow Impellers in a Pilot-scale Mixing Vessel. *Chemical and Biochemical Engineering Quarterly, 19*(4333-340).

Subrahmanyam, T., & Forssberg, E. (1988). Froth stability, particle entrainment and drainage in flotation — A review. *International Journal of Mineral Processing, 23*(1-2), 33-53. https://doi.org/10.1016/0301-7516(88)90004-X

Tabosa, E. (2012). *The effect of cell hydrodynamics on flotation kinetics.* PhD Thesis. The University of Queensland, Brisbane, Australia.

Trahar, W. (1976). The selective flotation of galena from sphalerite with special reference to the effects of particle size. *International Journal of Mineral Processing, 3*(2), 151-166. https://doi.org/10.1016/0301-7516(76)90031-4

Van der Westhuizen, A. (2004). *The evaluation of solids suspension in a pilot scale mechanical flotation cell.* MSc Thesis. University of Cape Town, Cape Town, South Africa.

Van der Westhuizen, A., & Deglon, D. (2007). Evaluation of solids suspension in a pilot-scale mechanical flotation cell: The critical impeller speed. *Minerals Engineering, 20*(3), 233-240. https://doi.org/10.1016/j.mineng.2006.08.019

Van der Westhuizen, A., & Deglon, D. (2008). Solids suspension in a pilot-scale mechanical flotation cell: A critical impeller speed correlation. *Minerals Engineering, 21*(8), 621-629. https://doi.org/10.1016/j.mineng.2007.12.010

Wang, S., Boger, D., & Wu, J. (2012). Energy efficient solids suspension in an agitated vessel–water slurry. *Chemical Engineering Science, 74*, 233-243. https://doi.org/10.1016/j.ces.2012.02.035

Warmoeskerken, M., Van Houwelingen, M., Frijlink, J., & Smith, J. (1984). Role of Cavity Formation in Stirred Gas-Liquid-Solid Reactors. *Chemical Engineering Research and Design, 62*(3), 197–200.

Wills, B., & Finch, J. (2016). *Wills' Mineral Processing Technology: An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery* (8th ed.). Butterworth-Heinemann. https://doi.org/10.1016/C2010-0-65478-2

Wu, J., Zhu, Y., & Pullum, L. (2001). Impeller Geometry Effect on Velocity and Solids Suspension. *Chemical Engineering Research and Design, 79*(8), 989-997. https://doi.org/10.1205/02638760152721857

Xu, D. (2011). *Factors Affecting Coarse Particle Detachment from Bubbles in Flotation, with a Specific Focus on Viscosity.* PhD Thesis. University of South Australia, Adelaide, Australia.

Zheng, X., Franzidis, J., Johnson, N., & Manlapig, E. (2005a). Modelling of entrainment in industrial flotation cells: the effect of solids suspension. *Minerals Engineering, 18*(1), 51-58. https://doi.org/10.1016/j.mineng.2004.06.002

Zheng, X., Franzidis, J., Johnson, N., & Manlapig, E. (2005b). *Modelling of Froth Transportation in an Outokumpu 3 m3 Tank Cell.* Centenary of Flotation Symposium. Brisbane, Australia.

Zlokarnik, N., & Judat, P. (1969). Tubular and propeller stirrers–an effective stirrer combinationfor simultaneous gassing and suspending. *Chemie Ingenieur Technik, 41*(23), 1270-1277.

Zwietering, T. (1958). Suspending of solid particles in liquid by agitators. *Chemical Engineering Science, 8*(3-4), 244-253. https://doi.org/10.1016/0009-2509(58)85031-9