

The relationship between particle size, cell design and air recovery: the effect on flotation performance

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Abstract

Froth flotation is an established method of separating mineral from its associated ore. Although there has been many years of research and development, there remains much room for development.

A 4 L bench-scale, continuously overflowing and recycling single species flotation system was developed for this work. It was used to investigate the effect of particle size and retrofit designs on air recovery, a measure of froth stability, as well as the solid and liquid flowrates of the system.

Particle size had an effect on air recovery and flotation performance. An increase in solids flowrate corresponded with a decrease in the particle size in the concentrate. When air recovery was below 50 %, the peak in solids flowrate corresponded with the peak in air recovery.

The addition of a retrofit design, a horizontal mesh of varying hole-size and thickness, was tested at a range of superficial gas velocities in a three-way full factorial trial. It was shown that a mesh of 30 mm hole-size and 40 mm thickness resulted in a statistically significant improvement in solids flowrate to the concentrate, when compared with the unmodified base case.

Position Emission Particle Tracking (PEPT) provided an opportunity to make qualitative and quantitative assessments of particle behaviour within the pulp and froth. PEPT data indicated that in the unmodified base case, swirl from the pulp continued in the lower froth, a behaviour never observed before. Variation in mesh hole-size lead to visible changes in tracer trajectories, and an increase in mesh thickness resulted in both tracers entering the froth more frequently.

This work has developed a novel experimental system capable of determining the effects of a range of operational and design parameters on air recovery and flotation performance, and has corroborated and justified the trends seen through statistical analysis and novel imaging techniques.

Declaration

I declare that no portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification at this or any other university or institute of learning. All work presented in this thesis is my own, except that which is appropriately referenced.

Alexander Norori-McCormac

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Chapter 1

Introduction

1.1 Motivation

Throughout history, there has been a demand for the Earth's minerals in order to augment and improve our standard of living. As the human population grows, communities modernise and quality of life for all improves, so does the demand for these raw materials, on which our society is built.

Resources are becoming scarce and their quality declines while global demand increases. At the same time, there has been a trend towards mining companies becoming more socially and environmentally responsible. These pressures have fed into research undertaken with the aim of improving both new and mature methods of mineral recovery.

One of those processes is known as flotation, a method of separating minerals on the order of 100 μm from their associated ores that makes use of hydrophobicity and flowing froths. The process was developed over 100 years ago; however, it remains rather inefficient with as much as 10 % of the mineral still lost regularly to the waste stream. Many of the sub-processes governing the observed behaviours are still poorly understood, and so enhancing our understanding will lead to improved sustainability, as well as performance and environmental benefits.

Many of the sub-processes are poorly understood due to the inconsistent nature of the ore fed to flotation cells. This makes it difficult, if not impossible, to develop an understanding at steady state. In addition, the time and cost involved in testing at an industrial scale can be prohibitive.

The first aim of this project is to develop a bench-scale experimental system that could operate continuously at steady state for an extended period. Previously, the majority of experimental work has been carried out in batch, making use of experimental systems such as Denver cells. This does not allow steady state to develop, which makes it difficult to study the effect of changes in air rate and particle size for example, on froth stability and operational performance. A system based on the stirred tank reactor of Costes and Couderc (1988) has been developed. The system recycles the overflowing concentrate as feed to the cell and allows steady state to develop and operate for a number of hours. Froth stability (a measure of performance) is measured making use of froth image analysis and the overflowing concentrate can be sampled for analysis. A second aim of this project is to determine what effects particle-size has on system behaviour. For the first time, the effect of particle size on flotation performance and froth stability have been studied with regard to air recovery. These results may allow us to optimise flotation operations to suit the size distribution of the feed to cell, reducing cost and improving performance.

There are opportunities to improve performance, not only through better understanding of operational parameters, but also through novel changes to the system set up. One such group of modifications are retrofit designs. These are cheap, quick changes to the cell design that may lead to performance benefits. The third aim of this project is to determine what effect a horizontal mesh of differing hole-size, thickness and position has on air recovery and flotation performance. Any improvements in either grade or recovery could be applied to flotation circuits, helping to improve the overall performance of the plant.

The effect of designs amongst other experimental parameters on particle behaviour is difficult to determine, due to the opaque nature of flotation froths. Computational modelling allows us to simulate what is going on. However, Position Emission Particle Tracking (PEPT) allows us to track particle motions within the flotation cell by the use of irradiated tracers. Pioneered in flotation by Imperial College (Cole et al., 2010, 2011; Waters et al., 2008,, 2009), PEPT can be used to determine what effect air rate and changes in flotation cell design have on particle behaviour and ultimately flotation performance.

The culmination of this work will provide an experimental system from which a whole range of flotation operating parameters could be investigated at steady state. It will provide new insights into how particle size affects froth stability and flotation performance. It will allow for an understanding of the effect of retrofit designs on flotation performance, providing cheap, alternative means to a costly plant refit. Finally, it will provide an understanding of many of the effects seen through modifying design through PEPT imaging techniques.

1.2 Organisation of thesis

This thesis is laid out as follows. Chapter 2 provides a review of the literature. Froth flotation and its role in the mining industry is outlined, followed by an explanation of the processes that govern flotation. The absence of particle size studies and their effect on froth stability and flotation performance is highlighted. Flotation cell design today and the minimal number of retrofit designs on the market today are discussed.

In Chapter 3, the development of a 4 L bench-scale recycling flotation system and the particle system with variations discussed for PEPT are presented. The application of measurement systems for air recovery and methods for physical sampling of the overflowing concentrate are then discussed. The development and production of retrofit designs is described, and the statistical analysis of the results associated with mesh designs presented. Finally, the PEPT experimental process and data analysis is discussed.

Chapter 4 presents the results of testing three different particle size distributions at five different superficial gas velocities. The results in terms of air recovery, solids and liquid flowrate, solids concentration in the froth as well as particle size in the concentrate are compared and discussed. Conclusions are drawn on the changing nature of the system with respect to the particle size of the feed and on the links between air recovery and flotation performance.

Chapter 5 outlines the factorial experimental trial undertaken, comparing a range of mesh designs in the flotation cell in terms of air recovery and performance with an unmodified system. The results are critically analysed, statistically validated and discussed, with the effect of mesh hole-size and thickness on air recovery, liquid recovery, solids content and indicative grade and recovery considered.

In Chapter 6, PEPT, an investigation into the effect of a range of mesh designs on the behaviour of hydrophobic and hydrophilic particles is discussed. The effect of swirl in the pulp is also presented. The performance of the mesh designs in the factorial experimental trials are critically evaluated with respect to the observations made using PEPT.

Chapter 7 is the final Chapter of this work. It presents the conclusions and potential future work is outlined. This includes developing a true experimental separation system and an investigation into particle shape and further development of the mesh designs. In addition, the case for a more suitable experimental system for PEPT experiments is outlined.

The appendices outline the bulk raw data for all experiments undertaken as part of these investigations and additional studies undertaken during the course of this PhD.

Chapter 2

Literature Review

2.1 Introduction

This Chapter introduces froth flotation, a method of separating minerals on the order of 100 μm from their associated ores. Flotation is a mature process (Wills and Napier-Munn, 2006) and is integral to mineral processing today. However, there is still a desire to improve as ore grades drop and separation becomes more costly. The flotation process will be discussed, focusing on froth stability, the behaviour of particles in pulp and froth phases and particle size effects. Air recovery, a measure of froth stability and flotation performance, will also be presented. Flotation cell design and current retrofit modifications will be discussed with a view to improving performance.

Positron emission particle tracking, PEPT, is a non-invasive technique that utilises an irradiated particle to determine particle motions within an opaque, multiphase system. PEPT has been used to determine the effect of changes in operating parameters on flotation performance, and the technique will be discussed here with reference to flotation specific applications in the past.

2.2 Mineral processing

The modern world is built upon a foundation of mining and metals. These raw materials are required to build the homes we live in, the infrastructure depended upon and the commodities desired in daily life. Mineral processing is integral to sustaining this way of

life. The majority of metals in use today are extracted from a host rock. Mineral processing describes the group of processes that refine the extracted ore into the final base product.

Mineral processing is a multistage operation, and different techniques are required for different minerals. However, they typically follow a similar separation process. First, the ore is mined, crushed, ground and milled. This is in order to begin liberating the valuable mineral. The next stage involves separating the valuable mineral particles from the waste rock or gangue. There are different methods for separating the mineral, exploiting the different properties of the mineral and the host rock. These include gravity separation, heap leaching (hydrometallurgy) and froth flotation (Wills and Napier-Munn, 2006). The concentrated mineral is then refined in order to produce the final high purity product (Wills and Napier-Munn, 2006).

This thesis is concerned with froth flotation as a separation process. Typically for flotation, ores are milled to an optimum particle size in the region of 100 μm (Jameson et al., 2007), the actual size determined by the surface properties of the mineral and the particle density. Following the concentration of the mineral in the flotation process, it is further refined into the final product, commonly through smelting (pyrometallurgy).

2.3 Froth flotation

Froth flotation is a widely used industrial separation process. Developed and patented over 100 years ago (Fuerstenau et al., 2007), the method is used to separate many different minerals, typically sulphides and oxides from their associated waste. Despite years of research, the process remains relatively inefficient and there remains room for improvement. The principles of flotation for mineral extraction are outlined below.

Liquid, typically water, is added to the milled ore in order to form a slurry. The slurry is conditioned with a collector, which preferentially adsorbs to the desired mineral surface rendering it hydrophobic, while leaving the gangue untreated. The slurry or pulp is then fed into a flotation cell (Wills and Napier-Munn, 2006). Here, a frother is added to the pulp, and is stirred with an impeller to ensure good mixing. Air is injected into the base of the cell, forming bubbles in the pulp. The mixing encourages bubble-particle collisions and large numbers of attachment occur (Wills and Napier-Munn, 2006). The frother reduces the surface tension of the liquid, aiding in bubble stabilisation (Bulatovic, 2007). These

bubble-particle aggregates ascend to the top of the pulp phase and form a mineralised froth above (Fuerstenau et al., 2007).

Gangue particles can also enter the froth through entrapment and entrainment between particles and in the liquid. The froth moves upwards due to the constant addition of stabilised bubbles at its base, and overflows the lip of the cell. The bubbles burst in the launder, recovering the mineral to the concentrate (Wills and Napier-Munn, 2006). A schematic of the flotation cell is outlined in Figure 2.1.

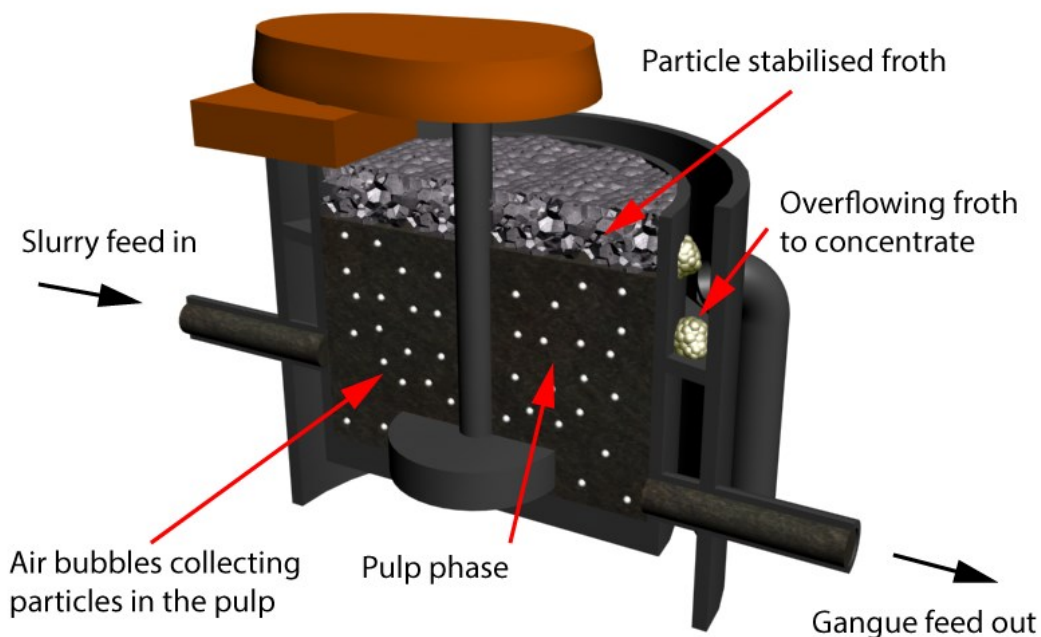


Figure 2.1 - Diagram of a flotation cell with the pulp and froth phases (research group image).

2.3.1 Particle hydrophobicity and attachment

The flotation process depends on differences in particle surface properties to operate. Klassen and Mokrousov (1963) noted the stability of froths is linked to the hydrophobicity of the particles. By rendering or increasing the hydrophobicity of a desired particle, its selectivity is enhanced by driving the particle towards the gas phase in a three phase (gas, liquid and solid) system (Gupta and Yan, 2006). A three-phase contact is shown in Figure 2.2, with the hydrophobicity of the particle determined by the contact angle (θ)

between the liquid/gas (γ_{LG}) and solid/liquid interfaces (γ_{SL}). The larger the contact angle, the greater the hydrophobicity of the particle (Gupta and Yan, 2006).

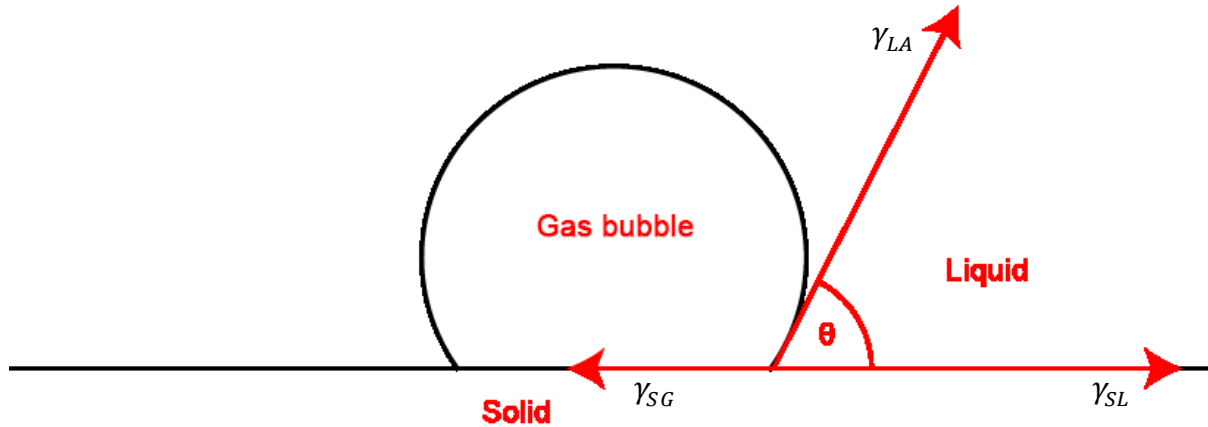


Figure 2.2 -The contact angle between a particle and the gas phase within a liquid [based upon Gupta and Yan (2006)].

In equilibrium, the contact can be described by Equation 2.1 (where γ represents the surface energy of the interface):

$$\gamma_{SG} = \gamma_{SL} + \gamma_{LG} \cos \theta \quad (\text{Equation 2.1})$$

In order to increase the hydrophobicity of the particle, a surfactant known as a collector is added, which modifies the surface activity of the mineral. This in turn alters the residual surface energy of the solid/air (γ_{SG}) interface. As summarised by Bulatovic (2007), the contact angle increases in response, rendering the particle hydrophobic.

The collector is added to the pulp slurry with the milled ore. Collectors are ionic, with a polar group (charged head) and a non-charged radical (uncharged tail), often a hydrocarbon. The uncharged tail is hydrophobic (Iler, 1979; Fuerstenau et al., 2007). Within the pulp, the polar group of the collector preferentially adsorbs to the mineral surface. Different types of collector react to the surface chemistry of the mineral in different ways; for example, anionic collectors such as xanthates undergo chemisorption to the surface of minerals via the sulphur atom in their polar group (Fuerstenau et al., 2007). The hydrocarbon tail is perpendicular to the mineral surface as shown in Figure

2.3. The adsorption to the mineral surface is preferential as it reduces the free energy more than a reaction with the water ions (Fuerstenau et al., 2007). The hydrocarbon tail is drawn into the air phase of the bubble due to its hydrophobicity. Once attached to the bubble, the buoyancy brings the mineral particles to the surface of the pulp, where a froth can develop (Fuerstenau et al., 2007). The choice and amount of collector depends upon its strength and the specific surface chemistry of the particle to be collected, the froth should only be stable enough to overflow before bursting in the launder (Wills and Napier-Munn, 2006). Processes and effects in the pulp and froth phase are discussed below.

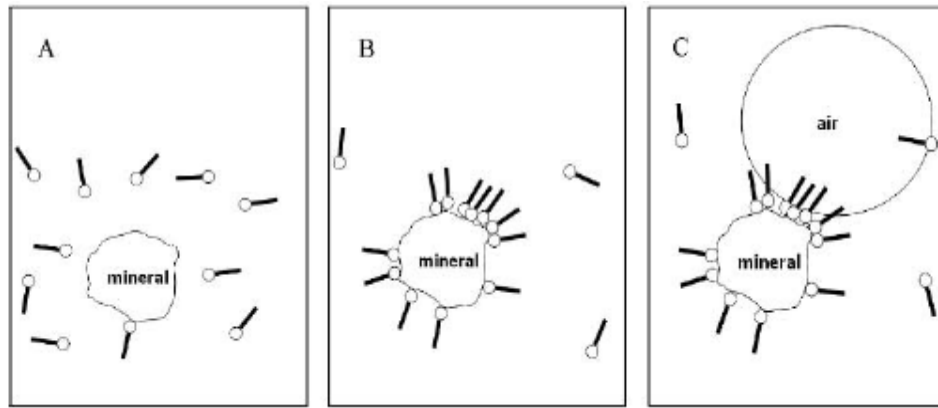


Figure 2.3 - "A: Collector dissolved in the aqueous phase, B: Adsorption onto a mineral surface and C: attachment of an air bubble onto the hydrophobic surface." (Gupta and Yan, 2006).

In addition to attachment, particles can be recovered through both entrainment and entrapment (Fuerstenau et al., 2007). Unlike attachment, neither process is selective nor do both contaminate the final concentrate with gangue particles. Entrainment is the uptake of particles into the froth phase, entrained within the liquid in the pulp. Entrapment is the capture of either mineral or gangue particles between particles attached to bubble films. These aggregates are then transferred to the froth phase (Gupta and Yan 2006; Wills and Napier-Munn 2006; Fuerstenau et al., 2007).

2.3.2 Pulp phase

The purpose of the pulp is to provide an environment for bubble-particle collisions. The pulp is a stirred and aerated slurry, consisting of milled and conditioned ore, mixed with water. Air is fed into the base of the flotation cell and forms bubbles within the pulp (Wills and Napier-Munn, 2006). An impeller stirs the pulp, suspending the particles. The action of the impeller shears the bubbles, increasing the total surface area available (Fuerstenau et al., 2007). The bubbles and particles come into contact within the pulp, with the

hydrophobic particles preferentially attaching to the bubbles (Fuerstenau et al., 2007). The bubbles rise to the surface carrying the attached particles and transfer to the froth phase (Wills and Napier-Munn, 2006).

The controls over particle attachment and detachment in the pulp are fairly well understood. Gaudin (1932) first identified the importance of bubble-particle interactions in the pulp phase. Sutherland (1948) theoretically described the attachment process of particles to bubbles, and further work by Schulze (1984), Dobby et al. (1986), Crawford and Ralston (1988), Hewitt et al. (1995), Nguyen (1997) and Nguyen et al. (1998) have refined these models. Pyke (2003) experimentally proved the attachment of particles to bubbles through film drainage during the sliding process. Further modelling work by Koh et al. (2000); Koh and Schwarz (2003) and Koh et al. (2009) modelled attachment as a function of cell design and hydrodynamics, though this has yet to be experimentally quantified. Koh and Schwarz (2003) also discussed how increased bubble density improves particle attachment in the pulp. Derjaguin and Dukhin (1993) discussed how particles near bubbles in the pulp must overcome different forces acting in three zones surrounding the bubble, before attachment can occur. The importance of surfactants in overcoming these boundaries to attachment was shown, as well as the difficulty fines and coarse have with successful attachment in the pulp. Derjaguin and Dukhin (1993) reinforced that there is an optimal particle size for mineral recovery from the pulp. This led to studies by Crawford and Ralston (1988) and Fan et al. (2010) that showed that coarse particles were less frequently recovered due to the mass of the particles causing them to slide along and detach from the bubble film, or be sheared away under turbulent conditions due to the centrifugal forces on the particle. van Deventer et al. (2002) noted that particles, particularly coarse particles were detaching at the pulp-froth interface. Jameson (2012a) showed that the poor recovery of coarse particles is related to the hydrodynamic conditions experienced in the flotation cell, particularly close to the pulp-froth interface. A study by Luttrell and Yoon (1992) showed that fine particles struggled to contact the bubble interface as they were deflected away in the slipstream of the ascending bubbles. The studies by Jameson and Luttrell and Yoon help to constrain an optimal particle size range for flotation.

Recent studies have focused on the more efficient capture and retention of mineral particles by bubbles. For example, Rahman et al. (2012) demonstrated in a small column that the addition of a small portion of fines to a coarse float significantly improves

recovery. Fan et al. (2010) have looked into the effects of nanobubbles attached to coarse particles in models and experimental flotation. This was with a view to improving particle capture in the pulp, with small bubbles adhering to the surface, assisting in the recovery of the particle through additional buoyancy effects.

The pulp phase processes have been extensively researched and the importance of the pulp in effecting particle collisions and collections noted. The effect of particle size on the collection process have been detailed extensively. It is noted that particle detachment is a result of the hydrodynamic (turbulent) conditions experienced at, or close to the pulp-froth interface. However, the mechanisms remain to be explored. There remains room for improvement in understanding how these parameters affect the rate of collection of particles in the pulp.

2.3.3 Froth phase



Figure 2.4 - Zinc flotation froth, Lisheen, Ireland (research group photograph).

The purpose of the froth phase is to recover mineral particles from the pulp into the overflowing concentrate. At the top of the pulp phase, the particle coated bubbles concentrate into a particle-stabilised froth, as shown in Figure 2.4. As the froth moves upwards, the liquid drains between the bubble lamellae, and the bubbles coalesce and grow. The majority of the mineral particles remain attached to the bubble films, whereas unattached particles drain away. The froth continually moves upwards and outwards due to the constant rise of bubbles from the pulp at its base, the net movement results in the overflow of the froth into a surrounding launder. Here the froth breaks down into a concentrate. As the froth phase is most significant in recovering desired particles, an understanding of the development and structure of the froth is required.

2.3.3.1 Froth structure and drainage

The structure of froth, a three-phase system consisting of solids, liquid and gas (Fuerstenau et al., 2007), is a dynamic one. To understand the structure, it is best to start with a study of a two-phase liquid and gas foam, as the nature of the structure is more easily observed.

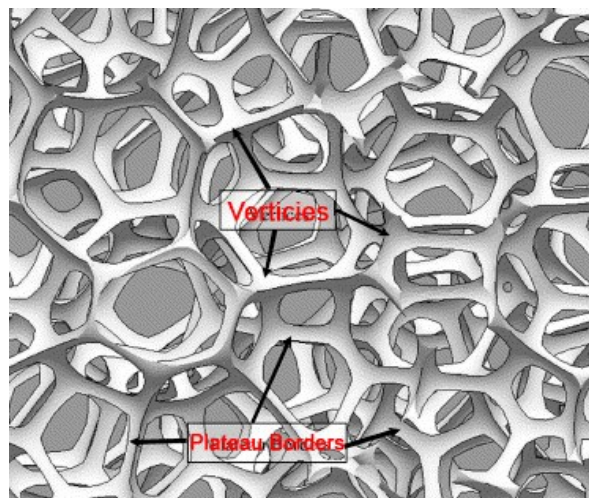


Figure 2.5 - Foam network structure (Neethling et al., 2003).

A foam consists of a range of polyhedral bubbles with numerous faces (Neethling et al., 2003). The bubbles films or lamellae are liquid filled passageways that form a network through the foam. At the nodes between three bubbles there exist Plateau borders and for four bubble contacts, vertices (Neethling et al., 2003). Liquid can drain through the foam network. A schematic of the network is shown in Figure 2.5.

The Plateau borders and vertices allow for the collection and storage of particles, and are important in entrainment and entrapment of solids in a froth (Neethling et al., 2003b). In most cases, liquid collects in the Plateau borders from the lamellae, and it is generally accepted that particles not attached to bubble films within the network settle within the Plateau borders.

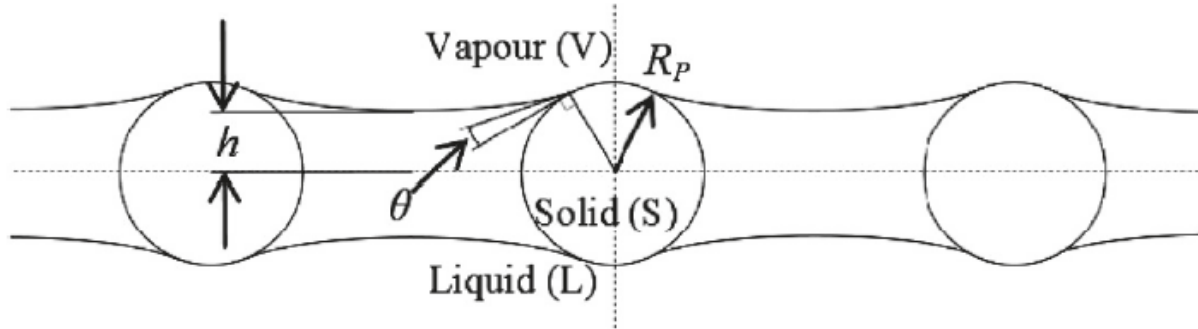
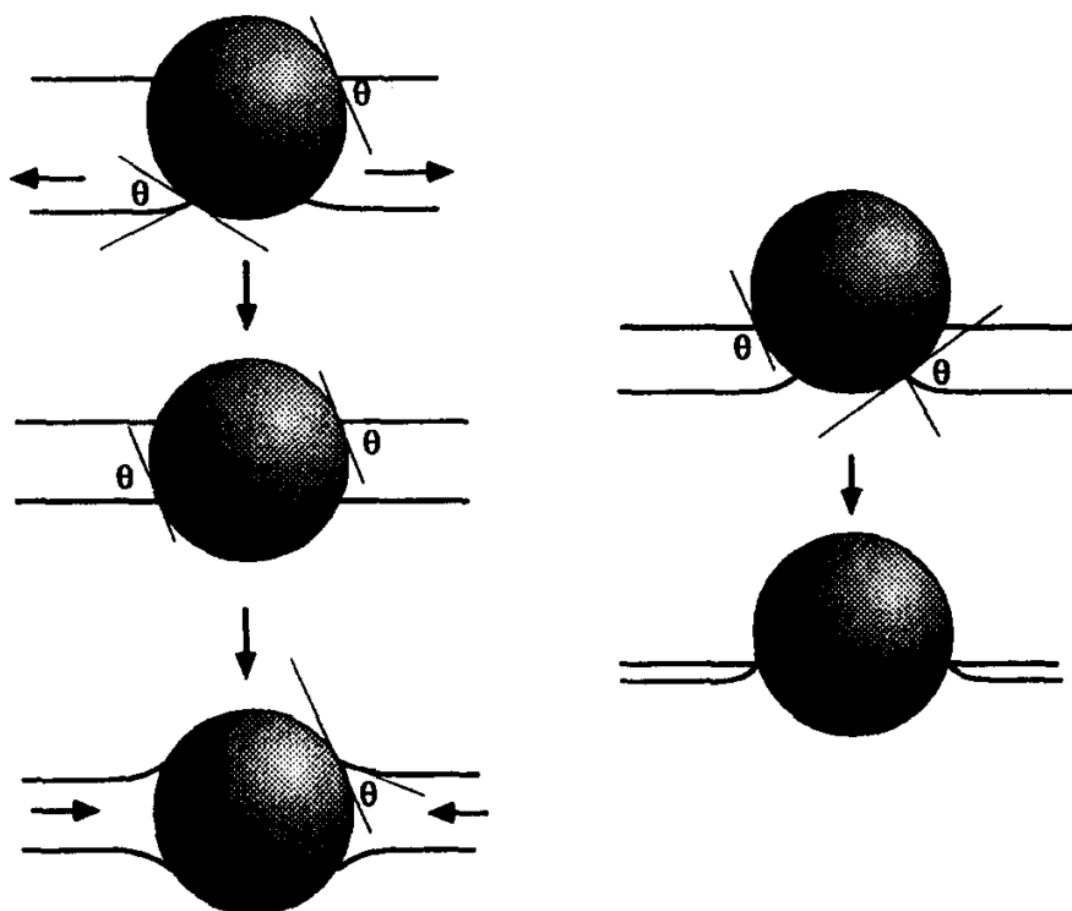


Figure 2.6 - A cross section of a particle-stabilised thin film. R_p is the radius of the particle, h is the film thickness and θ is the contact angle (the angle between the particle and the thin film of liquid). (Morris et al., 2011).

The addition of solid particles results in a froth that is a particle-stabilised foam (Wills and Napier-Munn, 2006), see Figure 2.6. The hydrophobicity of the particle will affect the stability of the film it is attached to (Dippenaar, 1982). Contact angles as discussed play a key role, and a range of contact angles have been suggested for optimal film stabilisation, with Aveyad et al. (1994) suggesting a contact angle of $85-90^\circ$, whereas Ata et al. (2003) suggest an angle closer to 66° . Contact angles in excess of 90° result in film rupture (Aveyad et al. 1994; Dippenaar, 1982), see Figure 2.7

Multiple attachment events stabilise the bubbles by bridging the film multiple times and inhibiting liquid drainage (Aveyad et al., 1994). This allows a froth to develop and overflow, as particle-stabilised bubbles accumulate and coalesce, with films able to drain to in excess of half the particle diameter thickness before they rupture (Aveyad et al., 1994), as shown in Figure 2.7. This increases the longevity of the froth structure.



(a) Contact angle of surfactant solution with particle, $\theta < 90$ degrees

(b) Contact angle of surfactant solution with particle, $\theta > 90$ degrees

Figure 2.7 - Diagram showing the bridging effect of (a), a hydrophobic particle with a contact angle of less than 90° and (b), a hydrophobic particle with a contact angle in excess of 90° . Note that for a, the liquid is drawn towards the particle with a thinning of the film, increasing stability by delaying film rupture. This allows particles of sufficient hydrophobicity to stabilise films for longer, sustaining froths (Aveyad et al., 1994).

As froths grow, their structure changes dynamically (Fuerstenau et al., 2007). At the pulp-froth interface, small heavily laden bubble-particle aggregates form a wet particle-stabilised froth that may be up to 36 % liquid at the pulp-froth interface (Neethling et al., 2003a). The bubbles form a dense network and move upwards. Continued drainage results in bubbles coalescing, bubbles bursting and particles dropping off into the film network, where they become entrained (Neethling and Cilliers, 2009). Excess liquid from ruptured bubble films drains through the Plateau borders, and entrained particles are flushed down towards the pulp and the gas holdup (the proportion of gas to liquid and solid) of the froth increases (Ireland and Jameson, 2007). Near the top of the froth, the

increased drainage results in thin walled bubbles, heavily laden with attached particles with lower mobility. It is towards the top where a distinguishable polyhedral network and bubble shape forms (Ross, 1997). Here the froth overflows the tank and the bubbles burst, recovering the mineral particles to the concentrate.

2.3.3.2 Froth stability

The study of froth stability has intensified over the last 20 years. Although lacking a widely accepted definition, it is related to the ability of a froth to grow and collapse, and it is significantly affected by the volume of solids in the froth phase (Fuerstenau et al., 2007). Investigations by Barbian et al. (2003) using a froth column tested a range of parameters to quantify froth stability. This led to the choice of air recovery, the proportion of air overflowing the lip of the flotation cell as unburst bubbles (Neethling and Cilliers, 2003), as a measure of froth stability. They also noted presence of a peak in the air recovery at intermediate air rates. Later studies by Barbian et al. (2006) and Hadler and Cilliers (2009) confirmed the existence of an industrial peak in air recovery. Hadler et al. (2010) and Smith et al. (2010) later recognised a peak in mineral recovery associated with the peak in air recovery. It has been determined that air recovery is linked to the volume of overflowing froth from the cell. Studies by Aktas et al. (2008) measured the froth stability using a modified froth column used by Barbian et al. (2003), in an experimental Denver cell with coarse particles. A decrease in dynamic froth stability in terms of air recovery with time was noted. However, the particle sizes ranged from 100-300 μm , outside the typical particle size range for flotation.

Attempts to quantify stability through air recovery and total mineral recovery have been successful, and the effects of operating variables such as froth depth investigated (Hadler et al., 2012). The effects of the particles has not been quantified experimentally or computationally. How particles affect froths at different air rates has not been studied, and how particle size affects froth stability and recovery forms part of this thesis.

2.3.3.3 Frothers

Frothers have a role in both the pulp and froth phase (Wills and Napier-Munn, 2006). The kinetics of the system are also altered by the frother, reducing the surface tension of the liquid, allowing easier bubble formation (Wills and Napier-Munn, 2006). Within the pulp,

the addition of frothers stabilises bubble formation, and it helps to generate and maintain a relatively stable froth (Bulatovic, 2007).

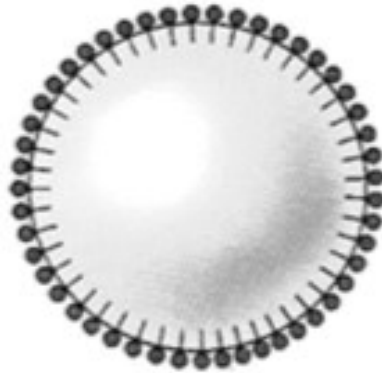


Figure 2.8 - Frother adsorbed to the liquid/bubble interface (Sam, 1995).

Frothers are chemically similar to some collectors, in that they are ionic, with a polar group (charged head) and a non-charged radical uncharged tail. Some frothers are powerful collectors, and so must be chosen carefully to ensure they do not affect the collection of particles (Wills and Napier-Munn, 2006). In solution, the frother will adsorb to the liquid/air interface as shown in Figure 2.8. The water dipoles combine with the polar group of the frother, hydrating them. The tail will then typically orientate into the air phase (Wills and Napier-Munn, 2006). This reduces the surface tension of the liquid and aids bubble formation. The coating of bubbles with frother also retards coalescence in the pulp (Khoshdast and Sam, 2011). In the froth phase, the reduced surface tension requires a larger differential stress to burst a bubble, increasing their longevity (Morris, 2010). A range of industrial frothers exist with differing chemistries, such as Dowfroth and MIBC for use in different flotation systems (Wills and Napier-Munn, 2006).

2.3.4 Particle size effects

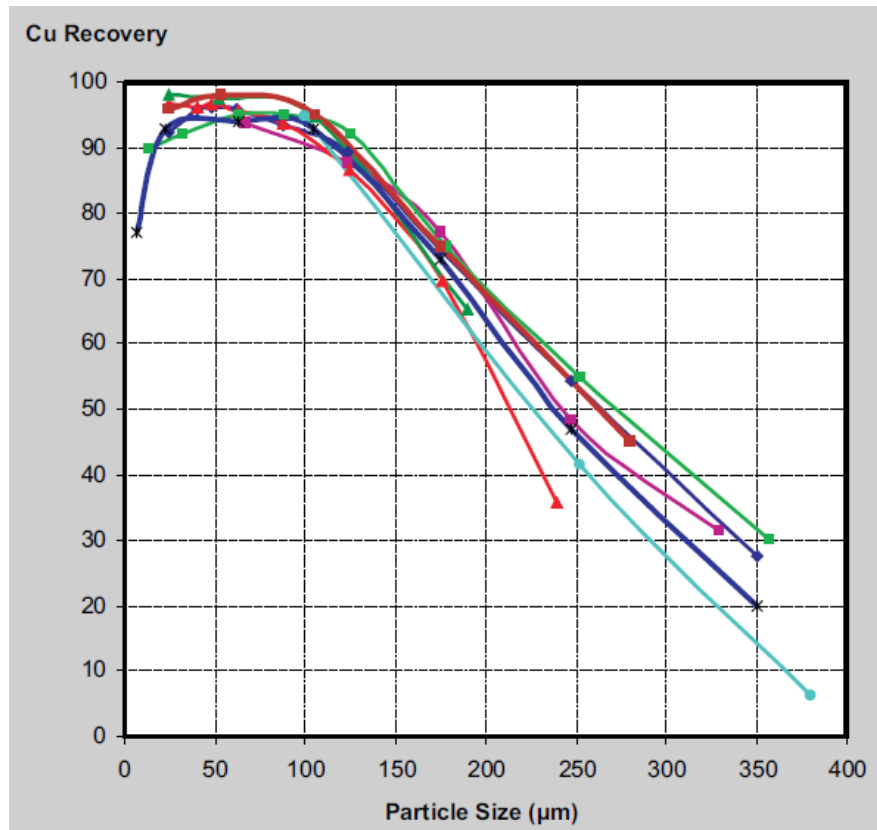


Figure 2.9 - Recovery of copper with increasing particle size in multiple flotation cells (Batterham and Moodie, 2005).

There is only a narrow range of particle sizes for which flotation is most effective (Fuerstenau et al. 2007; Wills and Napier-Munn, 2006), approximately 10-150 µm as shown in Figure 2.9. These values have not substantially changed in the last century, Gaudin and Malozemoff (1933) indicating an optimum size range of 10-50 µm, and current research suggests an effective range of 20-120 µm (Jameson et al., 2007). The particles of this size range frequently come into contact with bubbles and have a low enough mass not to detach under the turbulent conditions of the pulp (Tao et al., 2000). In the froth they stabilise the bubbles without bursting them, and also have a low enough mass not to fall back into the pulp (van Deventer, 2004).

The effects of particle size within the pulp are fairly well understood, however, how particle sizes stabilise or destabilise the froth has still not been fully resolved. As previously discussed, Klassen and Mokrousov (1963) noted the stability of froths is linked to the hydrophobicity of the particles, and this was further refined by Johansson and Pugh

(1992) who indicated contact angles of approximately 65° produced the most stable froths for fines (26 μm -44 μm particle sizes). Feng and Aldrich (1999) noted that intermediate sized particles are more easily recovered at bubble sizes more characteristic of flotation. They also indicated that particles with larger contact angles destabilised the froth and smaller contact angles did not affect the froth behaviour. Trahar (1981) noted that coarse particle recovery was more sensitive to the chemical environment than fines. Shannon and Trahar (1986) noted that coarse particles require considerably more collector for successful flotation, relative to the fine and intermediate size fractions. Crawford and Ralston (1988) indicated that particles of differing sizes require different hydrophobicities for optimum flotation, coarser particles requiring a lower contact angle for attachment. Soto (1992) noted that the froth phase was a barrier to the recovery of coarse particles, and Jameson (2012b) determined that the hydrodynamic conditions within the cell were the main control for the poor recovery of coarse particles. Jameson (2014) more recently showed that very coarse particles in excess of 400 μm can be recovered under conditions of low turbulence. The loss of particles at or near the pulp-froth interface remains unexplained. A link between the particle size distribution and the froth stability has yet to be made.

Further work attempts to link particle size to stability. Livshits and Dudenkov (1965) indicate an optimum particle size for bubble coalescence, coarse particles slowing the film drainage between bubbles and delaying coalescence, stabilising the froth, and fine particles draining away easily with little effect on the froth. Conversely, Szatkowski and Freyberger (1985) suggest that fine particles prevent coalescence and stabilise the froth phase. Moudgil (1992) details how coarse particles destabilise the froth phase. These investigations however have only linked stability through observation and system performance rather than an actual measure of stability. This is further backed up by Rahman et al. (2012) who state that coarse particles are very sensitive to changes in the froth and are difficult to recover, and that fines help recover coarser particles in increasing quantities. They also indicate that fines are much more easily recovered from the froth phase. Rahman et al. (2012) are not however concerned with froth stability but rather the how different parameters such as air rate and collector concentration ultimately affect particle recovery. Tao et al. (2000) observed how froth stability was a function of both the volume and size of particles in the froth phase, small volumes of coarse destabilising the froth, large volumes stabilising it, and very small sizes $< 30 \mu\text{m}$ destabilising froths in all

volumes. This study however is within very broad and separated particle size ranges, and does not observe how this stability factor changes with changes in size fractions.

It is clear from the studies undertaken that particle size does affect the froth stability and the total mass fraction of particles recovered from it. Attempts have been made to quantify the effects on particle size on froth recovery. However, the effect of particle size distribution on froth stability has yet to be quantified. In addition, the mechanisms behind the loss of particles near the pulp-froth interface, although shown to be related to hydrodynamic conditions in the flotation cell, have yet to be resolved.

2.4 Quantifying operational performance through recovery

In order to determine the performance and stability of the froth, measurements of air recovery, liquid recovery and froth (solids) recovery can be taken. These parameters are intimately related and are discussed below.

2.4.1 Air recovery

Air recovery (the proportion of bubbles that overflow the lip of a flotation cell) was first introduced by Moys (1984) and Woodburn et al. (1994) as a parameter that described froth stability. Early work by Ventura-Medina and Cilliers (2002) described changes in air recovery with variations in air rate. This was subsequently developed by Barbican et al. (2005) who noted similar trends in a froth column.

Hadler and Cilliers (2009) continued this work, noting an initial increase in air recovery with air rate, before a peak in air recovery for a particular air rate was encountered. This peak in air recovery was linked to a peak in the mineral performance of the system and froth stability (Hadler and Cilliers 2009; Hadler et al., 2010). This was a result of changes in froth mobility and behaviour as it responded to changes in air rate, the peak in air recovery providing a balance between solids loading on the bubble and flow of bubble surface over the lip of the cell (Hadler and Cilliers, 2009). Work undertaken by Smith et al. (2010) confirmed these observations utilising computer modelling to prove there was a peak in mineral performance associated with the peak in air recovery. Hadler et al. (2012) further demonstrated how other operating variables, in this case, froth depth, affect flotation performance and air recovery.

Air recovery is calculated as the velocity of the overflowing froth, multiplied by the overflowing cell lip length and the height of the overflowing froth and dividing it by the flow rate of air into the cell, as shown in Equation 2.2:

$$\frac{\text{Froth Velocity} \times \text{Cell lip length} \times \text{Overflowing froth height}}{\text{Air rate in}} = \text{Air Recovery} \quad (\text{Equation 2.2}),$$

where the air rate into a cell can be defined as a volume per unit time. In order to allow comparison across a range of sizes of cell (for which the air rate will inevitably increase with cell size), a value known as superficial gas velocity, J_g , is introduced. This takes into account the cross sectional area of the cell and the volume of air entering the cell per unit time as shown in Equation 2.3:

$$J_g = \frac{\text{volume of air per second}}{\text{cross sectional area of cell}} \quad (\text{Equation 2.3})$$

For flotation systems, a J_g on the order of 0.5-2.5 cms^{-1} is to be expected under typical operating conditions (Yianatos et al., 1988; Hadler and Cilliers, 2009; Smith et al., 2010; White, 2010). Measurements of froth velocity and overflowing froth height can be undertaken by the use of machine vision, a combination of a camera measuring the velocity of the froth and a laser recording the overflowing froth height (Shean, 2012). The cell lip length is usually known, but can be measured manually when required.

It is apparent that varying the air rate provides a method for finding the peak in air recovery and a peak in mineral recovery, and highlights the importance of studying the effect of other parameters (such as particle size and shape) on froth stability and mineral performance of flotation systems.

2.4.2 Liquid recovery

Neethling et al. (2003a) related volumetric liquid recovery to the air recovery of froths and foams, by combining simple relationships between the size of bubbles overflowing the lip of the cell and dimensions of the Plateau borders with liquid drainage equations. The investigation resulted in two formulae, one for below 50 % air recovery, and one for above 50 %. Neethling et al. (2003a) deduced that liquid recovery is linked to air recoveries below 50 %, but the two values become independent above 50 %. A typical industrial froth has air recoveries below 60 % (Hadler et al., 2010), therefore in most cases equation 2.4 applies, whereas equation 2.5 may apply more in experimental systems.

$$\text{Water recovery} = \frac{A_{cell} \cdot J_g^2 \cdot \lambda}{k_1} (1 - \alpha) \alpha \quad \text{for } \alpha < 0.5 \quad (\text{Equation 2.4})$$

$$\text{Water recovery} = \frac{A_{cell} \cdot J_g^2 \cdot \lambda}{4k_1} \quad \text{for } \alpha \geq 0.5 \quad (\text{Equation 2.5})$$

where J_g is the superficial gas velocity, A_{cell} is the cross sectional area of the cell, λ is the length of the Plateau borders per volume of froth, α is the air recovery and k_1 is the constant in equation 2.6 presented below:

$$k_1 = \frac{g \rho_f}{3 \cdot C_{pb} \cdot \mu_f} \quad (\text{Equation 2.6})$$

where g is the gravitational force, ρ_f is the slurry density in the overflowing Plateau borders, C_{pb} is the viscous drag coefficient and μ_f is the slurry viscosity. The formulae can be used as a check and balance for experimental and industrial systems (Neethling et al., 2003a).

Neethling et al. (2003b) noted that a decrease in air recovery lead to an increase in the liquid content of the foam above the peak in air recovery, but a decrease in the water recovery due to a smaller fraction of overflowing bubbles. Decreasing bubble size also increased water recovery. By measuring the air recovery of a system, and the average bubble diameter, an estimate for water recovery can be determined for an optimal system. By measuring water recovery experimentally, the two values can be compared to see how the system is performing (Neethling et al., 2003a). The experimental data can also be used to enhance modelling of flotation systems (Neethling et al., 2003b).

2.4.3 Froth (solid) recovery

Finch and Dobby (1990) define froth recovery as the proportion of mineral in the froth reporting to the concentrate. Froth recovery is a direct measure of the performance of a flotation system, indicating grade and recovery. Neethling (2008) defined it as the probability of an attached particle reporting to the concentrate, and links froth recovery to air recovery.

Neethling (2008) developed a simple model that would predict the approximate values of froth recovery for a range of operating conditions considering the probability of particle detachment and particles dropping out of the froth. Neethling (2008) suggests that the velocity of water increases in the vertical direction with bubble expansion because of particle drop off. Above where this velocity is equal to the settling velocity of the particle (the cut-off), the particle will be carried up and recovered, and below the particle will drop out of the froth into the pulp. This cut off point can be expressed as a bubble diameter within the froth, and the ratio between particles recovered and particles at the cut-off point describes the froth recovery (Neethling, 2008).

By using Equations 2.4 and 2.5 and solving this ratio, it is possible to express froth recovery as a function of particle detachment and the corresponding liquid response (Neethling, 2008). Similar to Equations 2.4 and 2.5, below an air recovery of 50 %, air recovery was linked to froth recovery as shown in Equation 2.7, whereas above an air recovery of 50%, froth recovery is independent of air recovery as in Equation 2.8.

$$Froth\ Recovery \approx \left(\frac{(1-\alpha) \alpha J_g \cdot}{v_{set}} \right)^{0.5 \cdot f} \left(\frac{d_0}{d_{surf}} \right)^f \quad \text{for } \alpha < 0.5 \quad (\text{Equation 2.7})$$

$$Froth\ Recovery \approx \left(\frac{J_g \cdot}{v_{set}} \right)^{0.5 \cdot f} \left(\frac{d_0}{d_{surf}} \right)^f \quad \text{for } \alpha \geq 0.5 \quad (\text{Equation 2.8})$$

where α is air recovery, d_{surf} is the bubble size on the surface of the froth, d_0 is the bubble size as it enters the froth, v_{set} is the settling velocity of the particles in the froth and f represents the fraction of particles that detach during a single coalescence event.

The research carried out by Neethling (2008) has linked air recovery and froth recovery. Direct measurements of the solids recovered indicate the amount and composition of

particles recovered. These direct measurements can be linked to changes in air recovery, which may indicate if the system is underperforming. The ratio of solids recovered to liquid recovered is also an indicator of system performance and is an easy way to check whether the froth is relatively stable.

2.5 Flotation cell design

Flotation in its current form was pioneered at Broken Hill in Australia beginning in 1902. By 1908 there was effective bulk flotation of zinc concentrate taking place (Fuerstenau et al., 2007).



Figure 2.10 - Bank of flotation cells, Mototolo, South Africa (research group photograph).

The basic design of the flotation cell has changed little since its introduction, with a stirred aerated flotation cell forming the basis for the process. Until recently most improvements came through scale-up of the cell design and large circuits as shown in Figure 2.10. Flotation however remains somewhat inefficient and there remain opportunities to improve the process. There has been an emphasis towards improving performance

through design as ore grades fall and separation becomes more costly. This can be either through completely new designs such as the Jameson cell (Clayton et al., 1991) and the Eriez Hydrofloat (Eriez, 2015), or through retrofit designs to the flotation cell. Current retrofit designs are outlined below.

2.5.1 Improving flotation through retrofit design

Retrofit designs allow for the possibility of improving performance at lower capital cost. Other ways of improving flotation performance have been explored. For example, improvements in selectivity and reagents, different arrangements of cells to maximise recovery from the slurry, increasing the size of cells, novel cell designs, improvements to the collection and handling of froth through launders and crowders as well as good control over the pulp and froth phases have all lead to improvements in operational performance.

There remains a drive to improve grade and recovery in the concentrate further, and one solution is through the application of retrofit design modifications to existing flotation cell configurations. These designs should be low in capital investment and easily implemented. There are avenues that have already been explored in the literature relating to retrofit or modified designs being applied to improve operational performance, and these are discussed below. Companies such as Outotec have undertaken considerable research into improving flotation through design. However, they are unwilling to disclose their exact designs and results for commercial reasons, in order to protect their investment.

2.5.2 Launders and crowders

Flotation cells remained relatively small until the 1970s, when there was a desire to increase the processing capacity of flotation plants. Increasing the size of the flotation cell was a first step (Fuerstenau et al., 2007). However, this increased froth volume did not lead to an improvement in recovery of mineral to the concentrate. The froth structure did not scale with the increase in size of the flotation cells, and large stagnant regions formed in the centre of the froth (Zheng and Knopjes, 2004). In order to recover the froth from these larger tanks more effectively, several retrofit designs were implemented, with the most successful being additional launders and the addition of crowders to the flotation cells (Fuerstenau et al., 2007).



Figure 2.11 - Radial launder in an Outotec flotation cell (own photograph).

Launders were proposed as it was noted that additional overflowing lip length was required to capture the additional froth being formed in the larger flotation cells (Arbiter, 1999). Multiple configurations have been implemented, including radial and doughnut (circular) launders as shown in Figure 2.11, which are positioned moving from the centre of the cell to the lip, and doughnut (circular) launders which are concentric rings placed some distance between the lip the centre of the cell. Both have proved effective in improving the recovery of froth to the concentrate.



Figure 2.12 - Conical crowder in an Outotec flotation cell (own photograph).

Crowders were implemented as a way of reducing the volume of froth at the centre of the flotation cell and directing this displaced froth towards the cells launders. The most common type of crowder is a truncated, inverted cone as shown in Figure 2.12, inserted into the froth zone at the centre of the cell. This directs the flow of froth upwards and away from the centre of the flotation cell. Crowders increase the total volume of froth for a given air rate, and reduce the amount of air required for effective cell operation, while reducing the amount of energy required to improve operation (Denger, 1997). Fuerstenau et al. (2007) described how a crowder modification lead to an 18 % improvement in recovery of mineral to the concentrate.

Combinations of launders and crowders were modelled by Neethling and Cilliers (2003), whereby they created 2D simulations of designs including different cone configurations and doughnut launders. The models indicated improvements in grade at expense of recovery for the designs. However, the models assumed that froth stability was independent of the modified designs and that bubble size was constant. In addition, the

designs apart from the donut launder were never tested industrially. Further studies were undertaken by Cole et al. (2011), whereby crowders were modelled in 2D and trialled experimentally. This sets the groundwork, there remains room for much more rigorous experimental study.

2.5.3 Mixing improvement and turbulence reduction

Launders and crowders are retrofit designs that influence recovery of froth to the concentrate. Other design modifications have modified behaviour in the pulp phase, either through improving the mixing behaviour, or by reducing turbulence, one of the major contributors to the loss of attached particles to bubbles.

The pulp phase is where particle-bubble collisions occur, and conditions should allow for as many collision events as possible. The mixing environment is determined by the type of impeller used and the shape of the flotation cell, circular or square. The majority of manufacturers employ a range of patented designs based on experience and research (Fuerstenau et al., 2007; Koh et al., 2000) that are designed to promote bubble-particle interactions and ensure material is transported to the froth phase as efficiently as possible.

One of the consequences of mixing using impellers is swirling of the pulp phase, where the fluid moves with the motion of the impeller (Rickard and Ralston, 1917). Vertical baffles promote mixing by breaking down macro circulation (swirl) in the flotation cell, increasing particle-bubble interactions (Yianatos et al., 2005).

These mixing environments are turbulent. Flotation requires turbulence to ensure particles have the greatest number of collisions with bubbles, particularly in the pulp and near the plane of the impeller (Fuerstenau et al., 2007; Wills and Napier-Munn, 2006). However, turbulence is also detrimental, particularly close to the pulp-froth interface, where the forces may lead to particle detachment (Jameson, 2012). Industrial designs have modified the turbulence profile of the flotation cell and increased attachment by enclosing the rotor or impeller in a stator (Fuerstenau et al., 2007). Some ideas remain relatively unexplored however, such as the horizontal baffle, or mesh.

Horizontal baffles have been tested in flotation columns that are not stirred by an impeller. Adjustable baffles were introduced by Kawatra and Eisele (1994). The baffle consisted of

a meshed or perforated plate across the column at various heights, breaking down the cross sectional area into many smaller mesh holes. This breaks up the bulk flow in the cell, affecting turbulence, and places an upper limit on the bubble size passing through that section of the column. Further research by Eisele (1999) showed a significant improvement in the grade of coal undergoing desulphurisation in a retrofitted flotation column, making use of horizontal baffles. They concluded reduction in churn was one of the key contributors to improved performance.

Separately, a study conducted by Zhang et al. (2009) introduced a honeycomb mesh with hexagonal cells into an industrial froth column as a packing material. The honeycomb was noted to be the most efficient shape with the lowest circumference to surface area ratio (Zhang et al., 2009). The aim of the honeycomb was to eliminate swirl in the upper section of the flotation column. The honeycomb resulted in laminar axial flow, little to no radial flow and improvement in the grade and recovery of the product recovered to the concentrate (Zhang et al., 2009).

Horizontal meshes have not been trialled in mechanically stirred flotation cells. However, the reduction in turbulence and improvement in grade and recovery noted in flotation columns by the use of meshes warrants further investigation through a retrofit design.

2.6 Positron emission particle tracking (PEPT)

Positron emission particle tracking, or PEPT, makes use of the near back-to-back γ -rays generated by the annihilation of a positron emitted from a radioactive source with an electron. These rays can penetrate opaque solutions and solid surfaces. This provides an opportunity to understand the motion of particles within systems, where previously it was only possible to simulate or make assumptions about.

PEPT was first developed at the University of Birmingham by Parker et al. (1993) as a derivative of positron emission tomography, or PET. PEPT makes use of a positron camera with γ -ray detectors (Parker et al., 2002). These detect the near back-to-back rays emitted by a radioactive material, allowing us to triangulate the location of the particle in space and time making use of a location algorithm (Fangary et al., 2002, Parker et al., 2002 and Barigou 2004). Tracer particles are composed of a porous resin that are labelled with a positron emitting radionuclide, typically either ^{18}F or ^{68}Ga (Fan et al., 2006a, 2006b; Cole et al. 2012) due to their relatively short half-lives.

The detection and data logging rate of the tracer must be maximised by achieving the highest level of activity. This improves the signal to noise ratio and provides higher sensitivity and data resolution. The algorithm developed by Parker et al. (1993) removes any corruption events as a result of Compton scattering and background radiation. The process has been validated by comparing observations of a rotating tracer to the PEPT data measured for the same event (Parker et al., 2002). The resultant error in position was noted to be approximately 0.6 mm, well within acceptable error given the nature of the experiments and systems to be examined by PEPT.

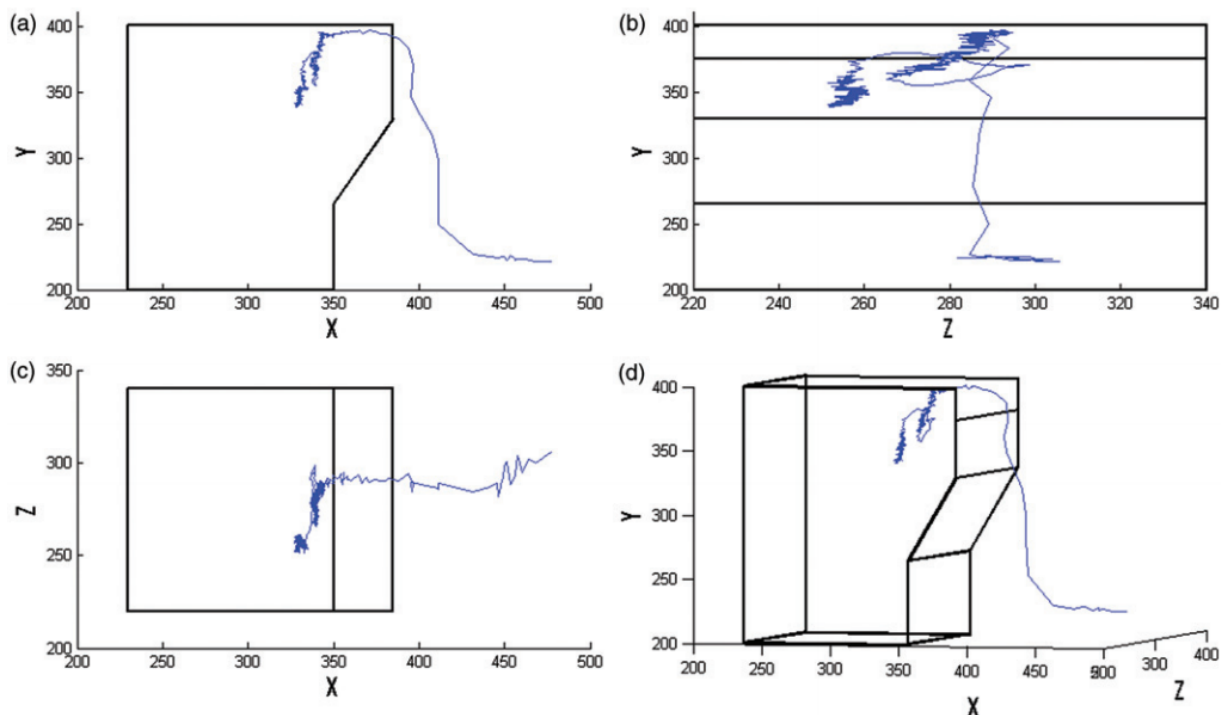


Figure 2.13 - PEPT Tracer motions inside a Denver flotation vessel (Waters et al., 2009).

The first successful application of PEPT to stirred systems was by Barigou (2004). There have been subsequent applications of PEPT across minerals processing, including physical separation processes; spirals (Boucher et al., 2014), hydrocyclones (Radman et al., 2014), comminution (Govender et al., 2010), as well as leaching (Ilankoon et al., 2013) and froth flotation (Waters et al., 2008, 2009).

The initial experimental work in flotation (Waters et al., 2008, 2009) made use of a labelled hydrophobic particle and hydrophilic particle in a true separation in a Denver cell. For the first time, particle behaviours such as bubble-particle attachment, detachment and motions within the froth phase were revealed, as shown in Figure 2.13. PEPT is

particularly useful for measuring particle effects in flotation froths as it is possible to modify the surface properties of the tracers in order for them to behave either as the desired mineral or gangue, hydrophobic or hydrophilic (Cole et al., 2014). Beyond the initial research, work was undertaken by Cole et al. (2010), investigating particle motions in a froth in a 2D column using PEPT. Subsequently, Cole et al. (2012) investigated the motion of particles in flotation froths.

There remains much scope for PEPT in flotation in determining how variables such as speed and occupancy as well as bulk flow behave with respect to different experimental configurations and tracer types. This study advances two areas of PEPT in flotation, firstly, turbulence on hydrophobic and hydrophilic particles will be examined close to the pulp-froth interface, and secondly, how the bulk flow and tracers are affected by the addition of retrofit designs to the flotation system.

Chapter 3

Experimental Methods with a Bench-scale Continuous Operation Flotation System

3.1 Introduction

This Chapter discusses the development and operation of a bench-scale flotation system. The methods for use in particle size effect and flotation cell modification testing, as well as PEPT are presented.

The experimental system fulfils several requirements. It is capable of producing a particle-stabilised froth. The experimental system achieves stability under steady state, in order to compare the performance between different experimental conditions over several hours. The experiments must also be repeatable. The system is limited in size by the field of view of the PET camera used in PEPT experiments. To this end a 4 L bench-scale recycling system, based upon a stirred tank reactor (Costes and Couderc, 1988) has been developed.

A single species silica ballotini froth has been developed. The single species allows fundamental insights into behaviour without the complexity of producing and analysing a true separation, and the associated uncertainties in the particle size distribution, liberation and particle shape. The feed samples are also reusable, providing the most consistent operation possible between experiments.

The system operates under typical industrial conditions (superficial gas velocities approximately $0.5\text{--}2\text{ cm s}^{-1}$). The system makes use of both a frother and a collector.

Performance is determined by calculating the air recovery of the experiments undertaken, making use of machine vision to record the necessary values. Data analysis is undertaken in MATLAB. In addition, physical measurements are taken using a 3D printed froth scoop, to collect samples of the froth for analysis.

A range of horizontal meshes of different hole-sizes and thickness have been developed for and tested in the experimental system. The meshes are 3D printed. This allows for a variety of configurations to be quickly designed and tested.

PEPT is employed under a strict set of conditions. The experimental system is a derivative of the system used for particle size and mesh design tests. The PEPT methodology, operation, and data analysis are also discussed.

3.2 Flotation cell design and impeller choice

3.2.1 Base case system

The design of the flotation cell and the choice of impeller affect froth stability because of the hydrodynamic state of the pulp phase. It is important to ensure good mixing in order to develop a particle-stabilised froth. The choice of cell and impeller must fulfil several criteria. It must ensure complete mixing of the solids and liquid. It must be easily repeatable, the hydrodynamics of the cell design must be well understood, and it must be easily modifiable. For these reasons, a design based on a standard tank reactor was chosen (Costes and Couderc, 1988).

The stirred-tank reactor (STR) was designed to result in a well-mixed contents (Schmidt, 1998). The design of the tank, or cell follows some basic design principles. The ratio of many of its components is in thirds, in order that the hydrodynamic conditions could be easily compared with existing models (Costes and Couderc 1988; Jenne and Reuss, 1999). The ratios of the design are as follows. The width of the cell is equal to the height of the liquid. The centre of the impeller sits one-third the cell diameter above the base. The design has been modified slightly from that of Costes and Couderc (1988) by lowering the height of the base of the impeller from one half to one third. This is to compress the flow pattern at the bottom of the tank to prevent settling. The impeller is one third the diameter of the cell (Jenne and Reuss, 1999). The baffles are one-tenth the width of the cell (baffles are in place to break the flow of liquid in the cell to prevent a

vortex forming). They are also the same height as the desired liquid level. The base design and modelled hydrodynamic conditions are shown in Figure 3.1 and Figure 3.2.

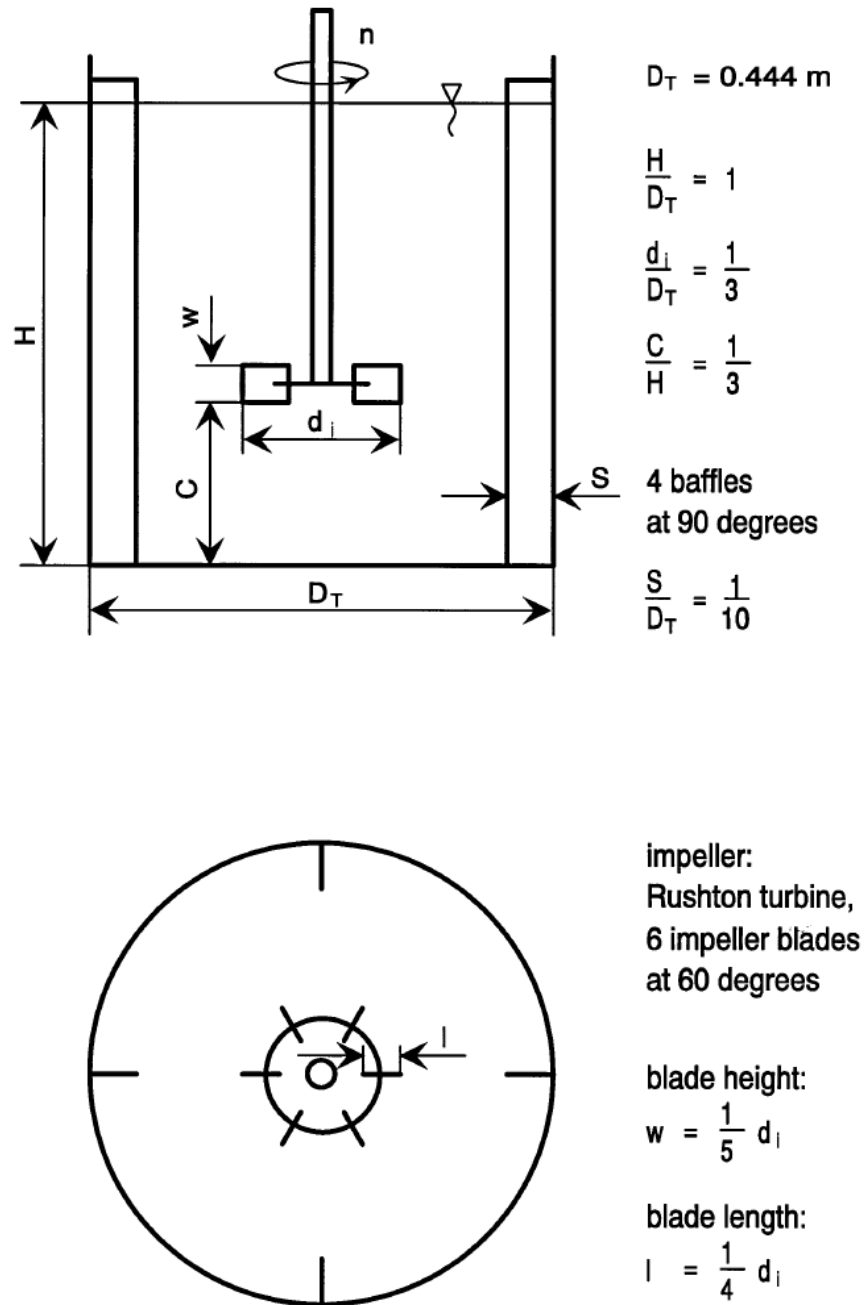


Figure 3.1 - Standard configuration for a continuously stirred tank reactor. Modified from Costes and Couderc (1988) and Jenne and Reuss (1999).

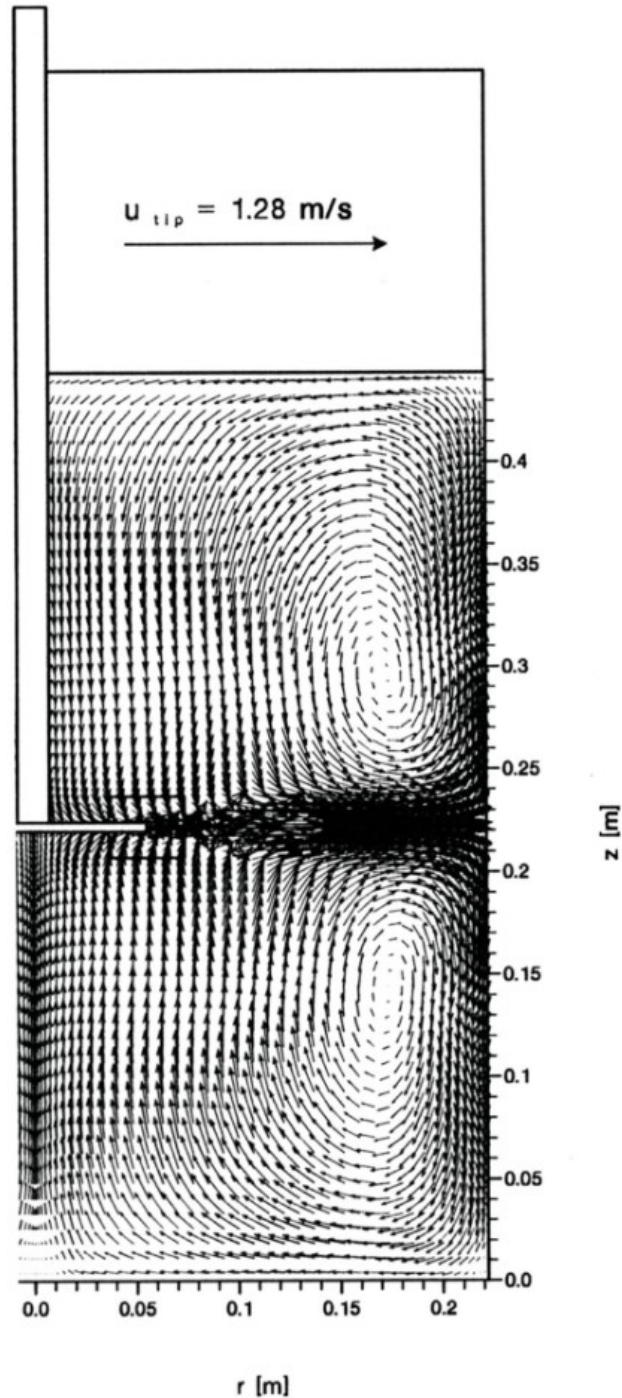


Figure 3.2 - Bulk flow within a continuously stirred reactor (Jenne and Reuss, 1999).

The design has been further modified from a mixing vessel to be compatible with flotation operation. The final design was a cell with a diameter of 180 mm, and is 180 mm in working height. The base of the vessel has been replaced with a multi-layered perforated frit (manufactured by Crabs Filtration Ltd), 110 mm in diameter, centred underneath the impeller shaft. Attached with a flange to the base of the cell is an air reservoir, 69 mm in height and with the same internal diameter as the cell itself. At the base of the reservoir

is an air inlet, connected to a manually controlled flowmeter with an operation range of 0-50 Lpm supplied by Key Instruments. The flowmeter was connected to an on-line air supply with a pressure range of 1-5 bar (air flowrate variable on aperture size).

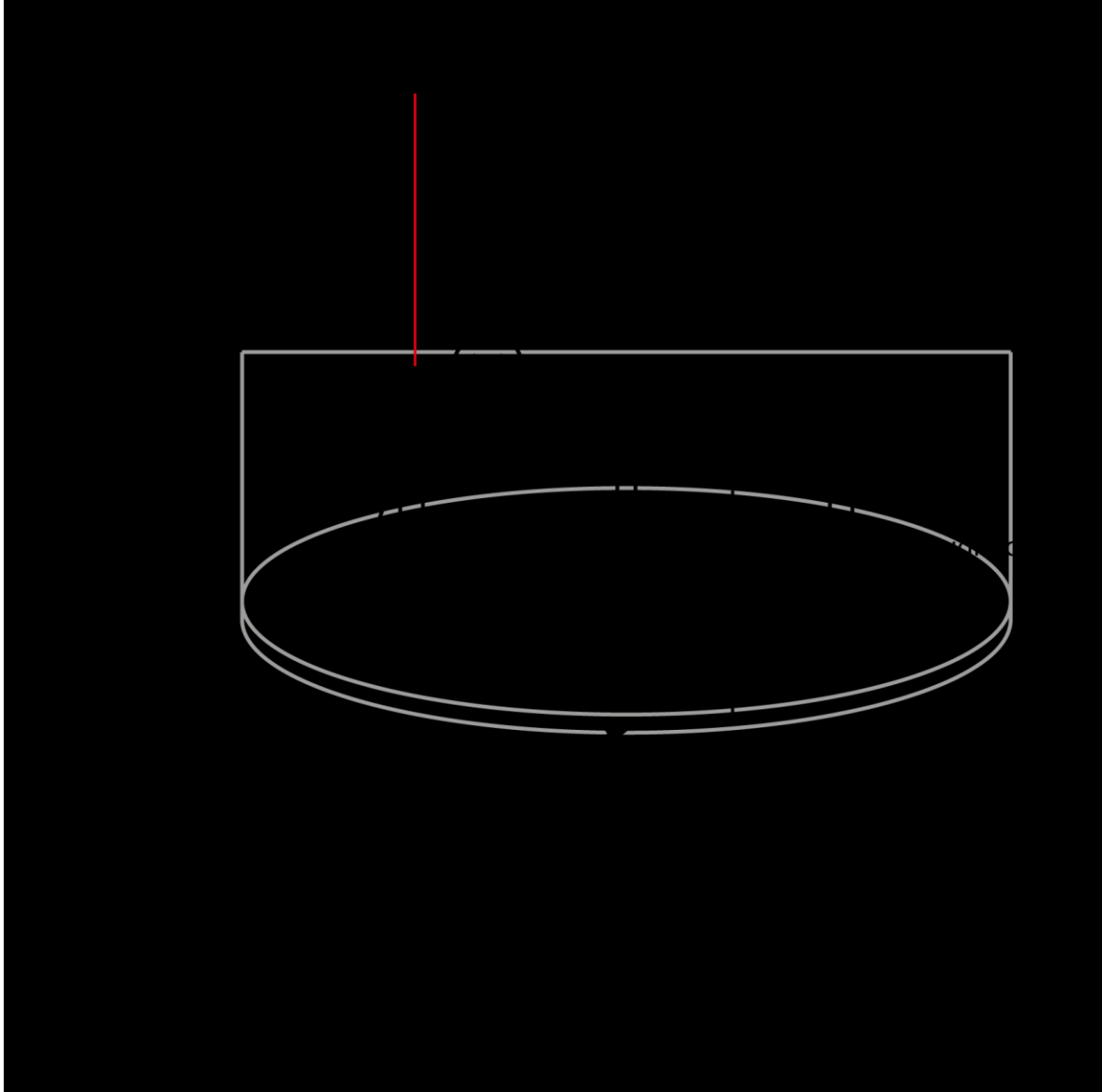


Figure 3.3 - Schematic of the 4 L bench-scale flotation cell developed.

Four baffles were fitted to the inside of the cell. The baffles extend to two thirds the height (120 mm) and are designed to prevent the formation of a vortex in the pulp phase. Fitted to the outside of the cell was a launder with the same volumetric capacity as the flotation cell itself. This launder is angled at 10° down from back to front. Overflowing froth as concentrate flows from the back to the front of the launder where there is an 8 mm outlet. This outlet is connected to tubing, passing through a Watson Marlow 505U peristaltic pump with a capacity of 2.2 Lpm, at maximum flowrate, at which it continually operates.

The inlet to the cell is centred at 60 mm above the base of the cell, in line with the plane of the impeller. A schematic of the flotation set up is shown in Figure 3.3 and a photo in Figure 3.4.

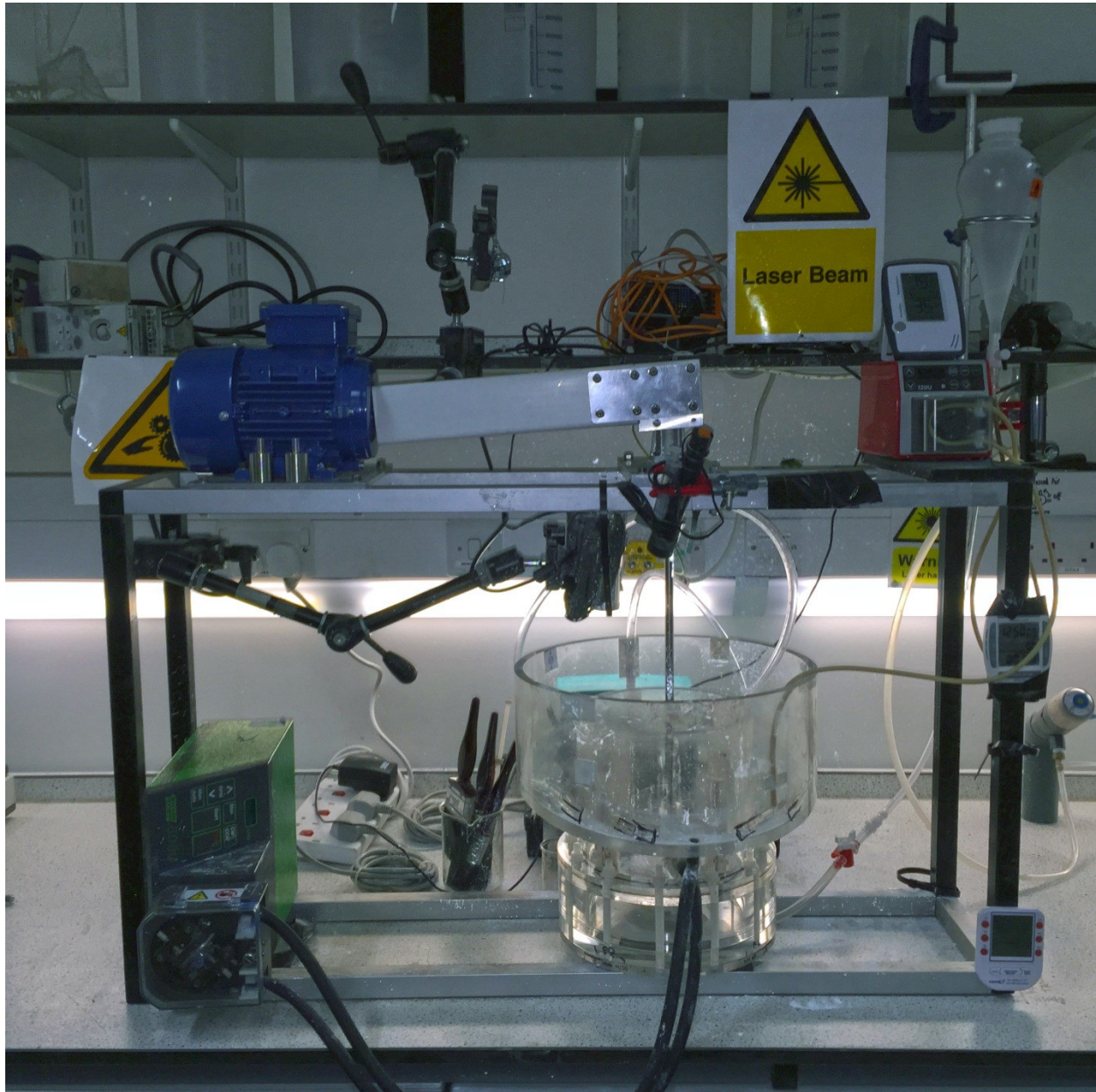


Figure 3.4 - A photo of the 4 L bench-scale flotation rig

In order to assist the recycling of concentrate from the launder, pulp was pumped out of the cell through a Watson Marlow 323 peristaltic pump with a flowrate of 2 Lpm. The pulp was pumped through an 8 mm Y nozzle at the back of the launder, and used to flush concentrate into the recycle for the cell. The two pumps working in tandem ensure the interface level between the pulp and froth remained at a constant height, as any increase

in concentrate flowrate does not affect the volume being recycled to the cell. The particles in the launder are transported towards the inlet for the recycle, ensuring the proportion of solids in the cell remained constant for steady state behaviour to develop.

Steady state operation requires dosing of frother to maintain stability. A Watson Marlow 120U pump was connected by 0.5 mm tubing to an inverted conical flask, with the outlet fixed to the inside of the launder, just above the inlet of the recycle. Frother was dosed to the experiment as appropriate.

The flotation cell was placed within a metallic frame, to which the motor, gearbox and impeller shaft are attached. The frame has dimensions of 940 x 220 x 560 mm. Fixed to the top of the frame is the motor supplied by Marelli Motori, connected to a 2:1 ratio angled gearbox (Automotion International Ltd). This then connects to the impeller shaft, at the end of which is a 60 mm diameter tip-to-tip Rushton turbine (impeller).

The choice of a Rushton turbine follows on from the configuration chosen by Jenne and Reuss (1999). The Rushton turbine is capable of mixing slurry well at low revolutions, and provides good gas dispersion, and shears bubbles (Jenne and Reuss, 1999). The Rushton turbine also provides tangential and radial flow in the cell, which divides, forming two circulating pathways vertically upwards and downwards, before recirculating back down towards the impeller (Jenne and Reuss, 1999). This resulted in a well-mixed pulp phase. As described by Pyke (2003), the cell is excellent at suspending and mixing material at the base of the cell above a certain rate of rotation, while also floating mineral well.

3.2.2 PEPT experimental system variations

There are several differences between the standard experimental system and the PEPT experimental system. These are detailed below.

In order to fit into the PET camera used in the PEPT experiments, the framework and equipment surrounding the experimental system was shrunk to a height of 360 mm from the previously described 560 mm. The length of the impeller shaft was also shrunk by 200 mm. The experimental system is otherwise similar. The reduced height results in less access space around the flotation cell, and necessitates a smaller camera to be fitted in order to record froth motion. The PEPT set-up is shown in Figure 3.5.

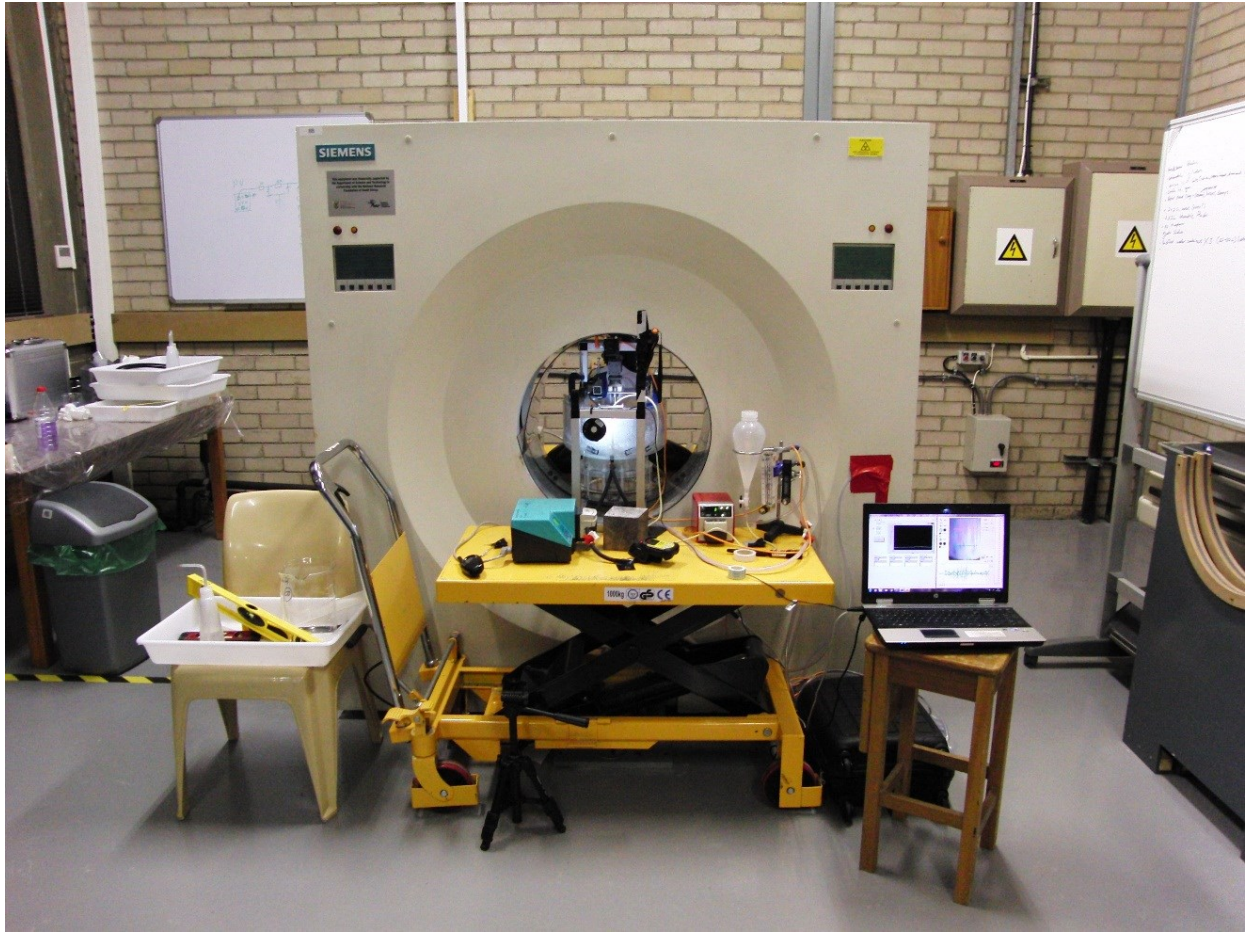


Figure 3.5 - PEPT bench-scale experimental set up

The launder was flushed with a 130 Lpm on-line air blow down system, rather than a pulp sourced wash-down. This consists of nine 6 mm nozzles connected to a separate on-line air supply and attached to the cell launder, at optimal positions from front to back. The flow of air from each nozzle was sufficient to move the concentrate from the back of the launder to the outlet for recycling.

3.3 Particle size distributions and flotation froth chemistry

3.3.1 Particle size distributions

A single species system was used for the flotation experiments. Changing the particle size or modifying the design of the flotation cell has effects on the performance of the experimental system. The benefits of a single species system include good particle size control, reduced costs, known properties of the chosen species and reusable samples. This improves the repeatability of the experimental system.

Silica ballotini produced by Sigmund Lindner were used, and have been used extensively in the past, for example Nguyen (1997), Ventura-Medina (2004) and Parida et al. (2006). The beads have a uniform rounded shape and chemistry. They were supplied in pre-sized sets, suitable for fundamental experimentation.

For the particle size tests in Chapter 4, four different particle size distributions or sets were formed. These were made up from pre-sized sample sets, and are summarised in Table 3.1. The coarse particle distribution formed the basis for the retrofit design tests in Chapter 5. A distribution with very coarse particles is used for PEPT, to match the tracer size, and is shown in Table 3.1. The particle size distributions of these mixed sets are shown in Figure 3.6 and Figure 3.7. Particle size distributions were determined using a Malvern Mastersizer 2000.

Table 3.1 - The five particle size distributions under investigation as part of this thesis

Particle sets	Components of the sets
Fine	900 g 40-70 μm
Intermediate	600 g 40-70 μm , 300 g 70-110 μm
Coarse	300 g 40-70 μm , 300 g 70-110 μm , 300 g 90-150 μm
Very coarse	300 g 70-110 μm , 600 g 90-150 μm
PEPT	450 g 100-200 μm , 450 g 250-500 μm

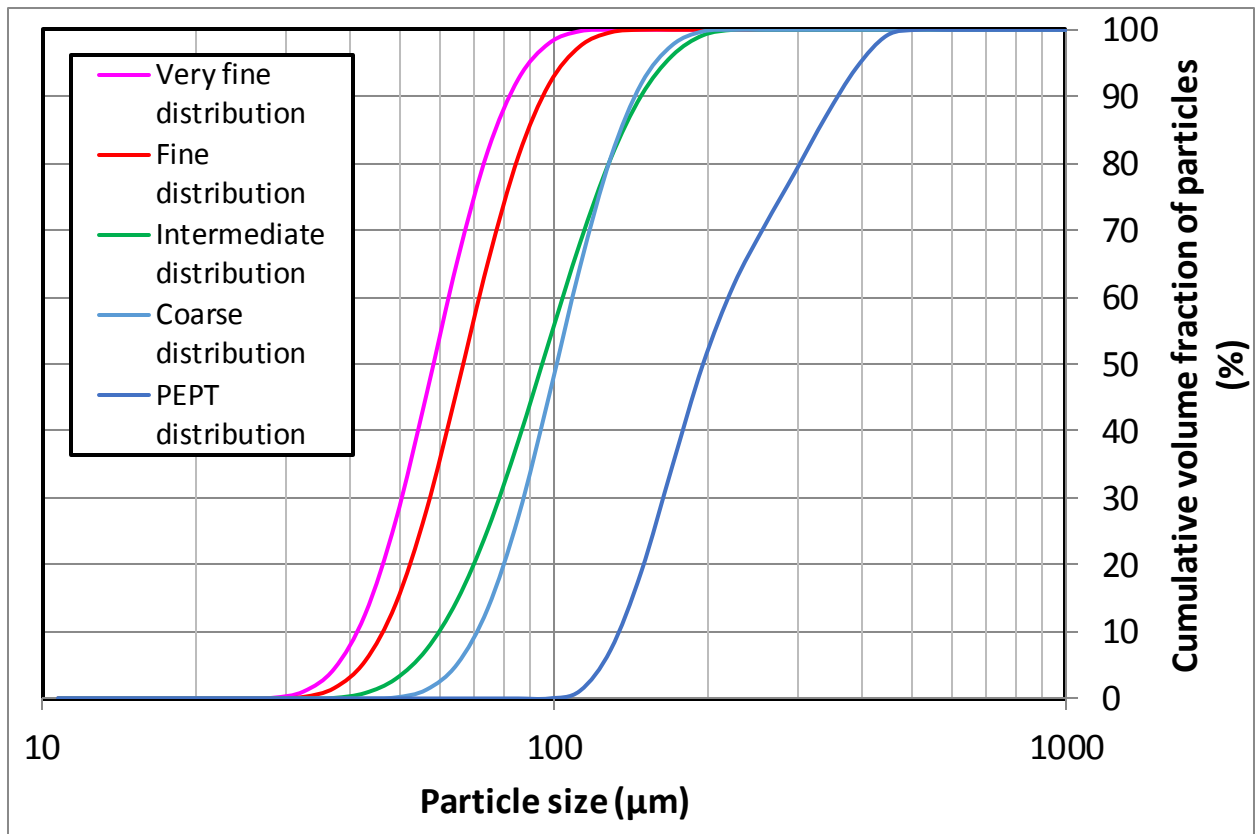


Figure 3.6 - Cumulative particle size distributions of the particle sets under investigation in this thesis.

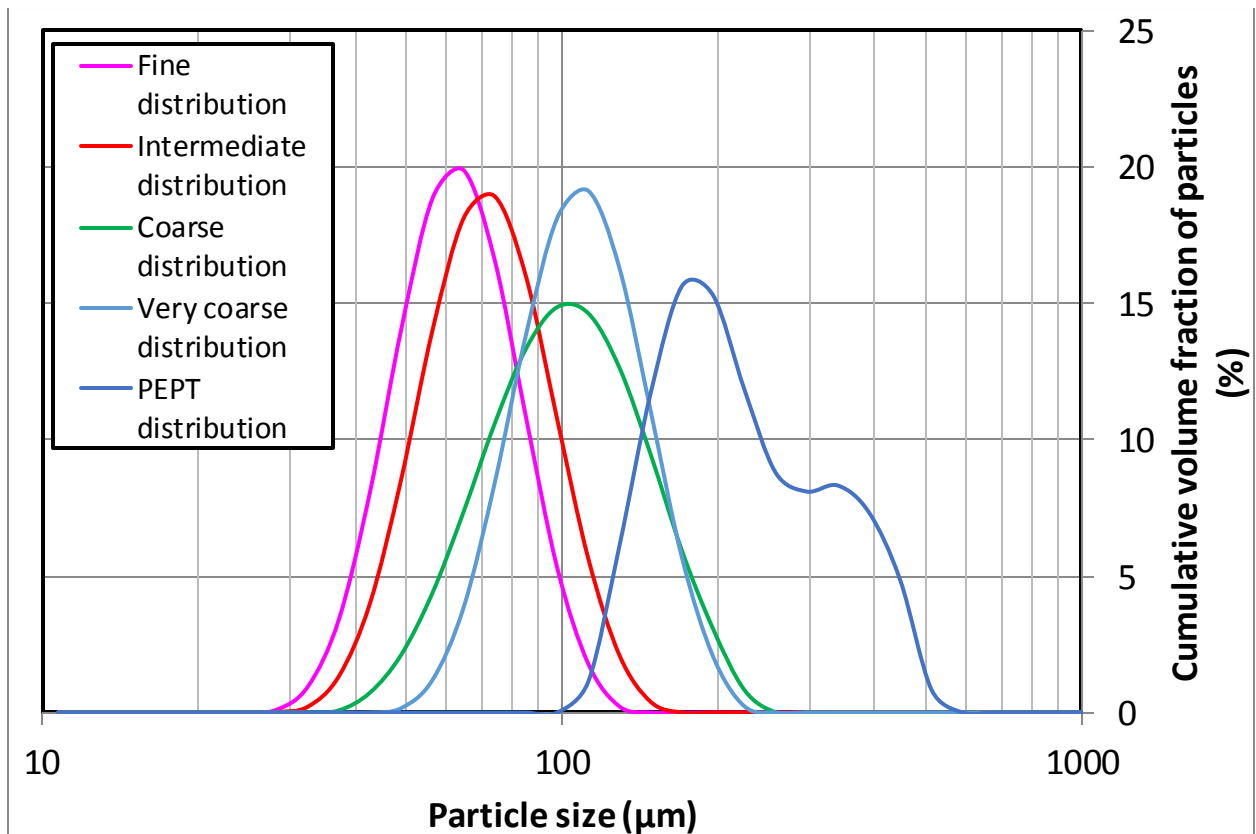


Figure 3.7 - Fractional particle size distributions of the particle sets under investigation in this thesis.

3.3.2 Flotation chemistry

It was desirable to replicate industrial flotation processes as closely as possible. Therefore, a frother-collector based system was developed for the experimental system. The system operates at a pH of 6.9 ± 0.1 .

The silica surface of the ballotini have a negative charge due to the presence of hydroxide (OH^-) molecules bound to the silicate structure. Myristyltrimethylammonium bromide, (TTAB), a cationic collector, was chosen for these experiments. The TTAB undergoes physisorption to the silica surface. TTAB is a member of a group of surfactants including Dodecyltrimethylammonium bromide (DTAB) and Hexadecyltrimethylammonium bromide (HTAB), which are used as collectors for negatively charged particles in suspension (Kruglyakov et al. 2004; Parida et al., 2006). Cationic collectors are problematic as they can act as frothers by hydrating the water molecules within the bubble films. The dosage of TTAB was determined and then strictly controlled in order to ensure the particles are sufficiently hydrophobic, but incapable of producing an overflowing particle stabilised froth without the presence of a frother.

A typically used industrial frother, Methyl isobutyl carbinol, MIBC (supplied by Sigma Aldrich), was chosen for the experimental system. MIBC is an alcohol, and has a tendency to vaporise rapidly under typical operating conditions (20°C , 30-40 % humidity), and so was dosed into the experimental system in order to maintain a stable concentration with time.

3.3.3 Sample preparation

Experimental samples were prepared as follows. The ballotini were added to the flotation vessel, and suspended in 2.9 L of deionized water with the impeller rotating at 915 rpm. An initial pH of 7.9 was required, and pH was determined by a pH probe held in the suspension; 1.2 mL of a 0.02 M solution of TTAB was added to the slurry and allowed to condition for 30 minutes. The pH of the system adjusts to 6.9 over this mixing period. At 30 minutes, 10 mL of a 0.1 M MIBC solution was added, and allowed to condition for a further 5 minutes. Following this period, the sample was ready for the experiment to begin.

3.3.4 Reuse of ballotini sample sets

The silica ballotini are reused in experiments. They must be cleaned between each experiment as the collector modifies the surface chemistry. The fresh ballotini were initially prepared by mixing with 2 L of deionized water and 10 mL of 1 M hydrochloric acid for one hour. This was followed by mixing with 2 L of deionized water with 10 mL of 1 M sodium hydroxide for one hour. The particles were then washed with deionized water to reduce the pH, and then mixed with 2.9 L of deionized water to form a slurry with a pulp pH of 7.9 in suspension. This reduced to a pH of 6.9 after 30 minutes of mixing.

After each experiment, the particles were mixed in 2 L of deionized water with 10 mL of 1 M sodium hydroxide for one hour. This resulted in the collector desorbing from the silica surface. The ballotini were then washed with deionized water and the pH reduced to 7.9 in suspension as previously discussed.

3.3.5 PEPT

The PEPT experiments made use of coarser particles to match the larger size of the tracers, and local tap water rather than deionized water due to supply constraints. This required a change in the flotation chemistry in order to float the ballotini successfully.

As with the standard procedure, 2.9 L of water was added to the ballotini in the experimental system. The particles were suspended at a pH of 9.0 at the desired impeller speed. 25 mL of 2 mM TTAB solution and 25 mL of 0.1 M MIBC solution was added and the experiment allowed to condition for 10 minutes. Large quantities of the collector and frother were required to float the ballotini successfully. Air was added at the desired air rate after 10 minutes, and the system allowed to condition for a further 5 minutes. At 15 minutes, dosing of the experiment with MIBC at a rate of 10 mLh^{-1} began. Experimental measurement can also begin at this time.

3.4 Operation

The impeller speed was set to 915 rpm for experimental operation. The equivalent electrical frequency as displayed on the control box for the motor is 32 Hz. After 35 minutes of conditioning has occurred, the air inlet was opened and air was added at a rate of 20 Lpm, the equivalent of a superficial gas velocity of 1.31 cm s^{-1} . At the same time, the peristaltic pumps associated with the experiment were switched on. The system

was allowed to then condition for a further 10 minutes with air, before the experimental procedure begins. The addition of air to the pulp resulted in a particle-stabilised froth forming above it. This overflowed and recycled as feed to the flotation cell.

There were a total of 45 minutes preparation and conditioning time for the system. At this point, the experiment is dosed with MIBC at a rate of 4.2 mLh^{-1} of the 0.1 M solution. This ensures that the system was relatively stable over the experimental period, as shown in Figure 3.8.

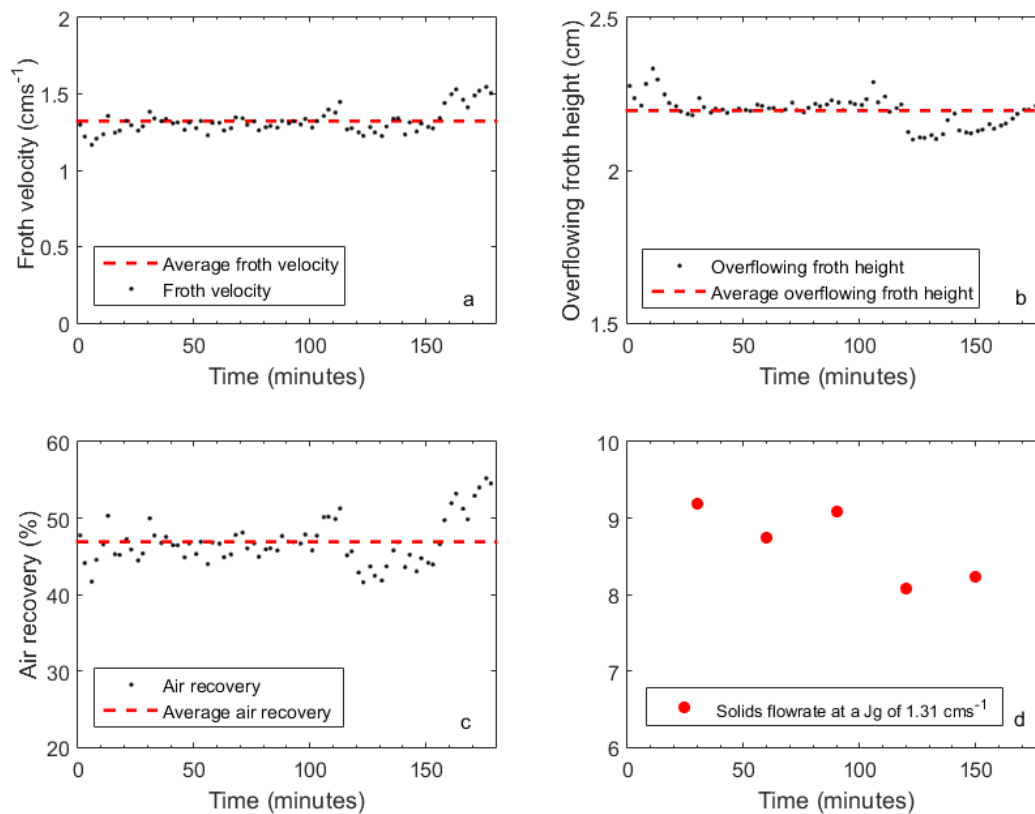


Figure 3.8 - Five second average of froth velocity (a) overflowing froth depth (b), air recovery with time (c) and solids flowrate (d) with time for the experimental system at a J_g of 1.31 cms^{-1} and a coarse particle distribution, indicating the system is operating at steady state.

As can be seen in Figure 3.8, this novel experimental system results in robust steady state conditions over extended periods of operation. Froth stability measurements are consistent as shown by the froth velocity and overflowing froth height, as well as providing consistent solids content in the concentrate. Extended study of operational variables such as particle size and shape, which have not previously been studied, can be undertaken.

Following the initial conditioning period, a new air rate, randomly selected from the values in Table 3.2 (depending on the experiment type) was selected. The selection of air rate was based upon the values being randomly selected in an excel spreadsheet.

Table 3.2 - Air rates run for each of the experiment types under investigation

Experiment type	Range of air rates (and superficial gas velocities)
Particle size	10, 15, 20, 25, 30 Lpm (0.66, 0.98 1.31 1.64 1.97 cm s^{-1})
Design	15, 20, 25 Lpm (0.98 1.31 1.64 cm s^{-1})
PEPT	21 Lpm (1.38 cm s^{-1})

After a change in air rate, the experimental system was allowed to condition for 5 minutes. Following this, a measurement period of 5 minutes is undertaken. Once complete, a physical sample of the overflowing concentrate was taken, and the system then switched to the next randomly selected air rate. The process was then repeated. The initial air rate was repeated at the end of the experiment to ensure there has been no significant degradation in the experimental conditions with time. Following the end of the experiment, the system was flushed with deionized water and the particles were prepared for the next experiment.

3.5 Experimental measurements

3.5.1 Data logging

Experimental conditions were noted on a log sheet prior to the experiment beginning, including the sample in use, design being tested, and the quantities of reagents used. pH and pulp temperature were monitored during the conditioning stage. During the experiment, manual froth depth measurements were taken. In addition, the temperature and humidity of the room during each stage of the experiment was noted. The time of each measurement was noted. Any other experimental factors or problems were noted on the log sheet as well. Physical measurements of the concentrate were also noted after they were taken (see subsection 3.5.3).

3.5.2 Air Recovery

The froth velocity, depth of overflowing froth and the cell lip length was recorded for each experiment to calculate air recovery. Froth velocity was determined using an in-house

block matching program known as Froth Tracker (as shown in Figure 3.9). A camcorder, (Panasonic Video NVGS37), was fixed above the lip of the flotation cell at a known distance, and provided a live feed to the program. In the PEPT experimental system, the Panasonic camera was replaced with a HP webcam, as its reduced size allowed it to fit inside the PET camera. The region of interest was illuminated with a lamp to improve the image contrast. A time-averaged readout of froth motion in frames per second was output as a list of values. These values were then converted into centimetres per second.

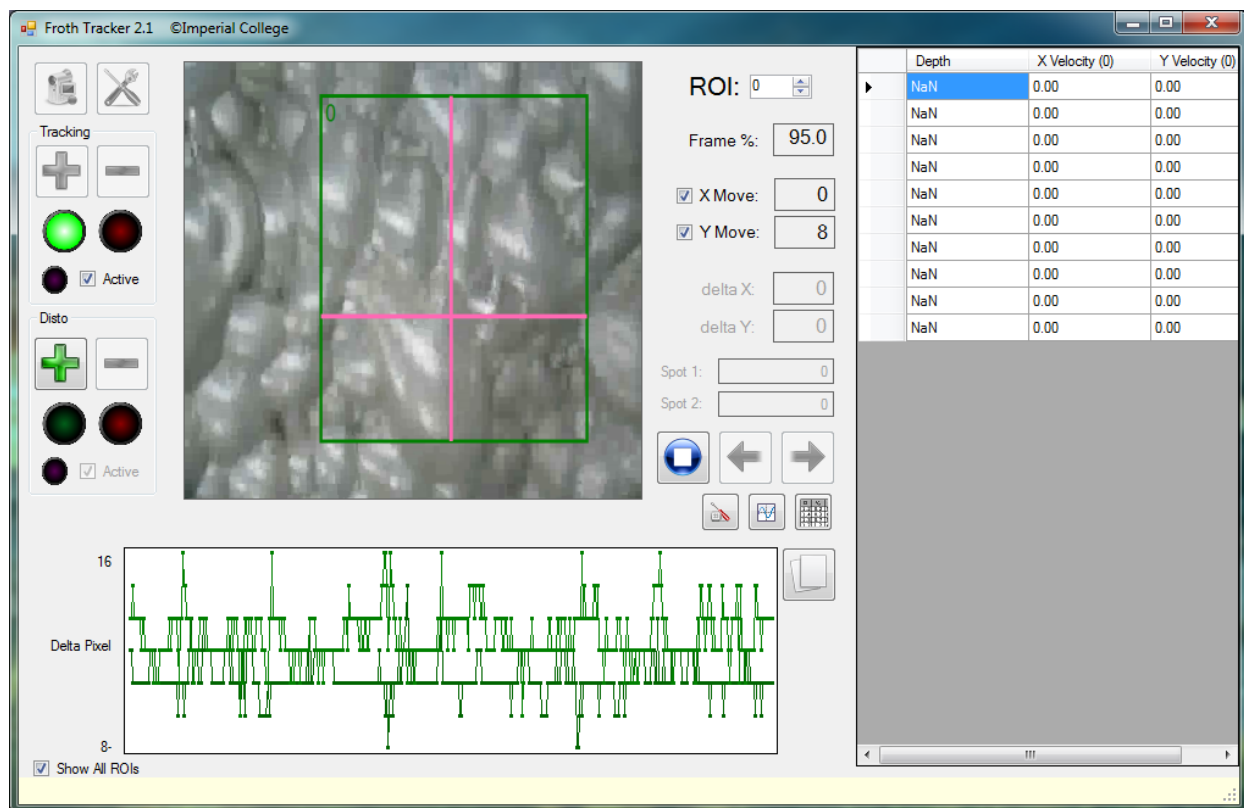


Figure 3.9 - Froth tracker v2.1. Algorithm tracks bubble surface motion as pixels/frame and outputs an average value that can be converted into cms^{-1} . (Imperial College, 2012).

Overflowing froth depth was measured in two ways. Manual measurements were taken, making use of a ruler sitting on the lip of the flotation cell. The height was measured to the nearest mm at the start and end of the 5 minute run. A laser also measured the overflowing froth depth. The advantage over manual measurements is that the laser could pick up variation in froth depth with time. However, the laser was susceptible to variations in the composition of the froth and variations in surface coatings of the bubble films with solids. This may lead to inaccurate readings. The fixed position of the laser was also problematic when running the experimental system at extreme conditions when testing

design configurations, as they may result in adverse performance, or the froth may not have been overflowing at the location of the laser.

An on-line laser, supplied by ifm electronic (model OD1300) supplied overflowing froth depth measurements to LabVIEW. The LabView program was based upon one used by (Shean, 2012). A script was written to collect 35 readings over 5 seconds and then provide an average froth depth measurement for the time interval. The output file was in the same listed spreadsheet format as that provided for the froth velocity.

The final component, overflowing lip length, was visually observed and noted. The lip of the cell was marked at 18° intervals (each equivalent to 5 % of the total lip length). Under operation, the number of segments not overflowing were counted to determine the percentage of the cell not overflowing. In addition, any segments also showing intermittent overflow (overflowing for approximately every 1 of 2 seconds) were noted and accounted for by assuming it overflows only 50 % of the time. The final value was recorded as a percentage.

By inputting these three quantities into equation 3.1, a value for air recovery for each experimental condition was determined.

$$\frac{\text{Froth Velocity} \times \text{Cell lip length} \times \text{Overflowing froth height}}{\text{Volume of air in}} = \text{Air Recovery} \quad (\text{Equation 3.1})$$

where the volume of air entering the cell is given as a volume in cm³. These quantities were calculated from the raw data, post-processed and read by a MATLAB script. For each experiment, the superficial gas velocity was plotted with air recovery. There is a maximum value for air recovery, and this is the peak in air recovery, PAR, for that particular system. This is consistent with the greatest solids flowrate, assuming a particle-stabilised froth (Hadler and Cilliers, 2009).

3.5.3 Concentrate flowrate

The concentrate flowrate was determined by sampling the overflowing froth, after the 5 minute logging period for air recovery. For this purpose, a sampling scoop was custom designed and 3D printed, as shown in Figure 3.10. The scoop occupied one quarter the length of the cell lip, and was attached for 20 seconds. For the PEPT experimental system, a smaller scoop was devised, being one eighth the lip length of the flotation cell. The scoop was again attached to the flotation cell for 20 seconds. The concentrate

accumulated in the scoop, which was then removed. The scoop and its contents were weighed. The contents was then emptied into a glass-measuring cylinder, where the solids were allowed to settle. A volumetric measurement of the solids and liquid content were then made.



Figure 3.10 - 3D printed scoop sitting inside the flotation cell launder

The concentrate weight was determined from deducting the weight of the scoop from the weight of the sample. The liquid was decanted and weighed. In order to calculate the weight of solids in the concentrate, the weight of the scoop and the weight of liquid were

deducted from the weight of the total sample. This was periodically checked by drying a sample and weighing it. It was found that the error was no more than $\pm 5\%$.

The liquid was added and sample agitated in order to suspend the solids. A small sample ($< 1\text{ g}$) was then taken from the suspension for particle size analysis for the particle size experiments. The remaining suspension was then returned to the feed to the flotation cell.

All the recorded measurements were added to a spreadsheet. The values could be read by a MATLAB script and then plotted and compared in a similar fashion to air recovery. Conclusions regarding concentrate flowrates and air recovery within and between experiments could then be made.

3.5.4 Particle size distribution

Small ($< 1\text{ g}$) samples of the feed, as well as samples from the overflowing froth were taken from each experiment. These samples were then analysed making use of a Malvern Mastersizer 2000 for their particle size distribution.

The sample was added to the Mastersizer via the Hydro SM small volume, entry level wet dispersion unit. The unit contained a small impeller and deionized water. The sample was suspended for analysis.

The samples were analysed using laser diffraction. The samples passed through an optical bench, where the particles were illuminated by the laser. The intensity of the scattered light as measured and used to determine the particle size distribution of the sample. The samples could then be compared.

3.5.5 Grade and recovery

A single species system cannot give a direct indication of grade and recovery, as there is no separation. However, comparisons can be made by comparing the solids percent in concentrate with grade, and solids flowrate with recovery, as demonstrated below.

3.5.5.1 Indicative grade

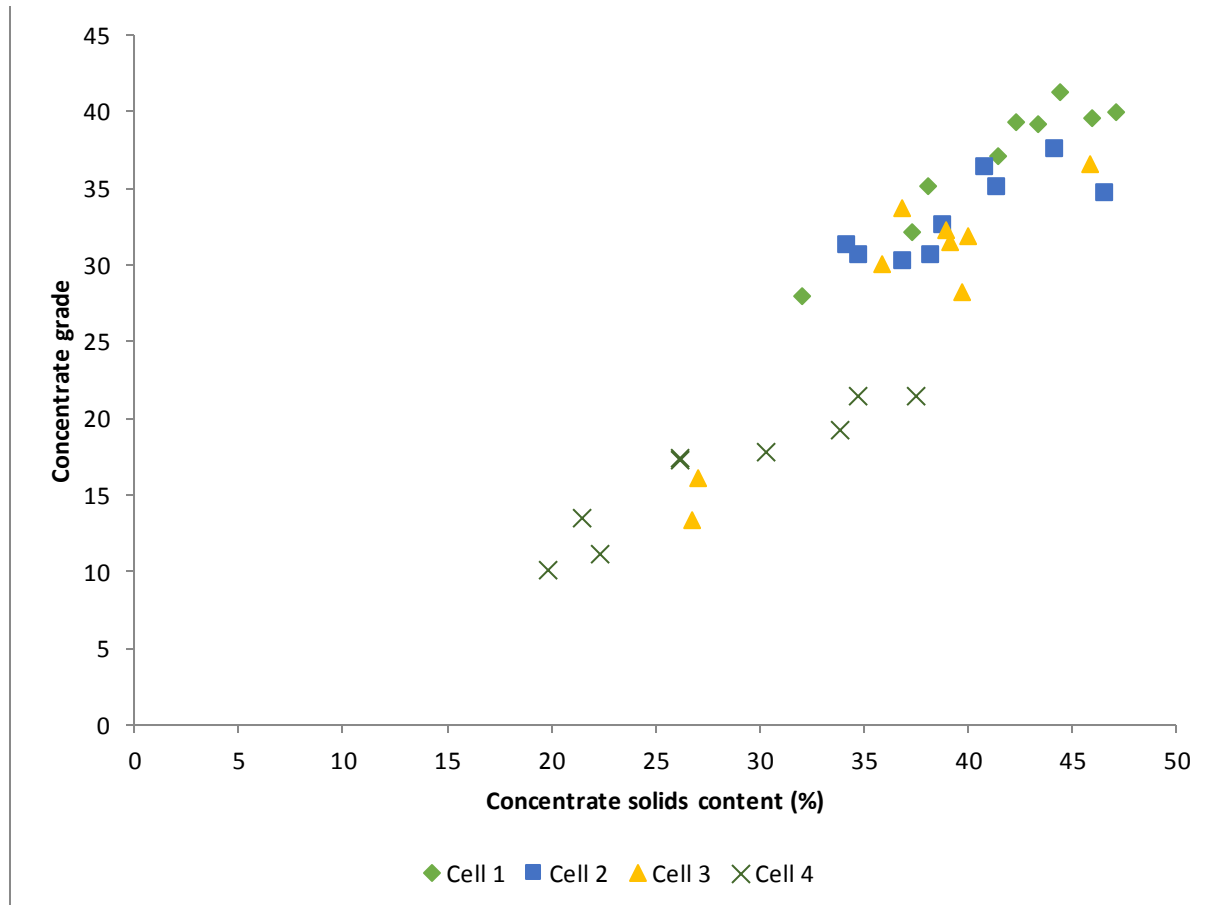


Figure 3.11 - Concentrate grade with concentrate solids content (research group plant data).

As can be seen in Figure 3.11, there is a linear relationship between concentrate grade and the solids content in the concentrate across a bank of flotation cells. This relationship exists in plant data from more than one source. Solids content in the concentrate can be used as a proxy for grade in the single species system. This is referred to as indicative grade in the discussion.

3.5.5.2 Indicative recovery

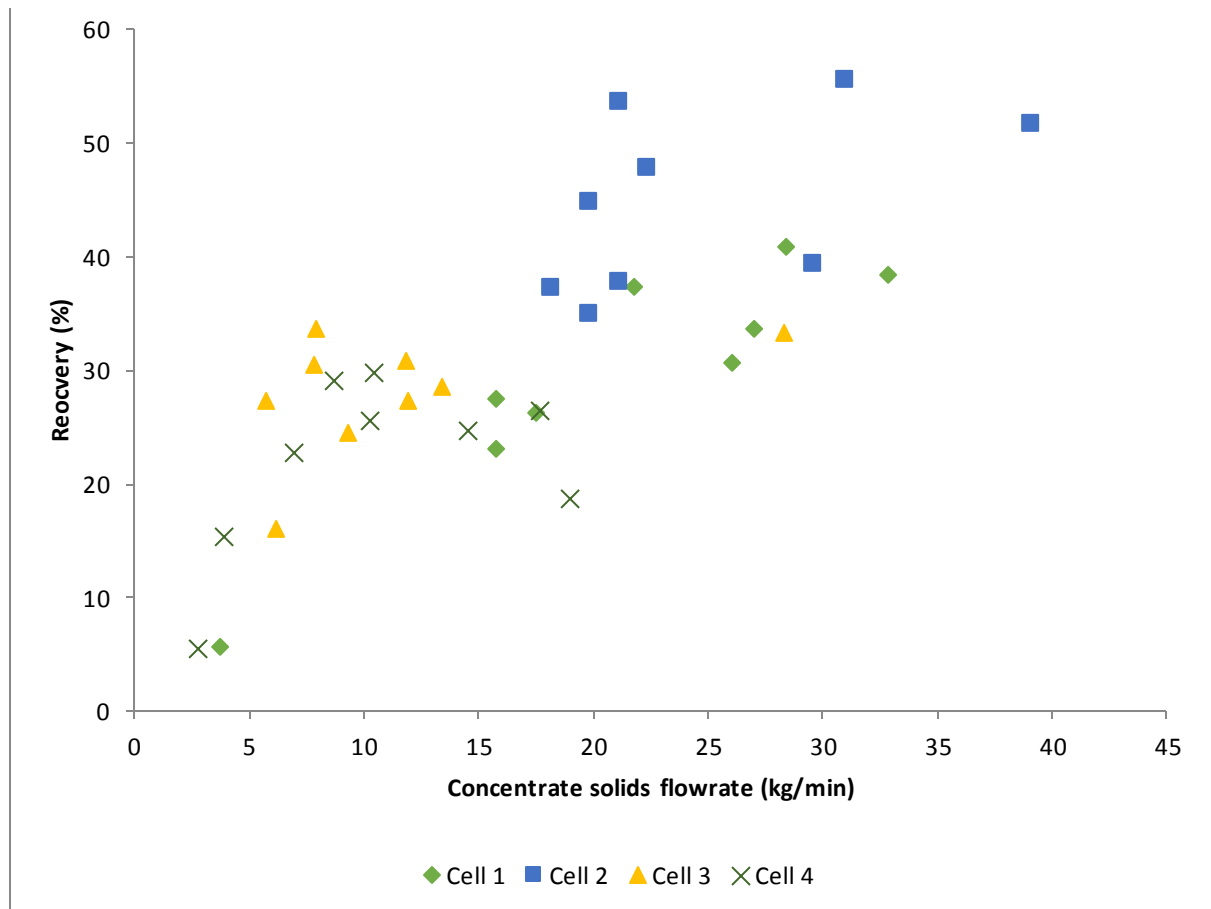


Figure 3.12 - Recovery of solids in concentrate with solids flowrate (research group plant data).

As can be seen in Figure 3.12, there is a linear relationship between concentrate grade and the recovery and the solids flowrate. This relationship is observed across plant data, from multiple sources, and allows the use solids flowrate as a proxy for recovery in the single species system. This is referred to as indicative recovery in the discussion.

3.6 Factorial experimental design trial and statistical analysis

In order to investigate design modifications to the flotation cell in a disciplined and efficient manner, a full factorial design was established. This allowed for a complete exploration of the effects of varying the value or level of more than one factor at a time. A horizontal mesh of varying thickness and hole-size design was investigated by this experimental factorial trial. The factorial designs are discussed below.

3.6.1 Factorial experimental trials

Three parameters (factors) were investigated. Mesh hole-size, mesh thickness and superficial gas velocity (J_g). Each of the factors can be investigated at different levels (sizes/magnitudes). An analysis of variance (ANOVA) is implemented once the factorial has been explored. This was in order to determine the statistical significance of any trends observed in the datasets, be they independent trends associated with a single factor, or interactions between the different factors. Other statistical tests, such as a t-test and Dunnett's method have been undertaken to compare between designs for significance (Napier-Munn, 2014). The factorial design is set out as in Table 3.3.

Table 3.3 - Mesh combinations tested in the three-way factorial. M refers to mesh, the first number represents the mesh hole-size and the second mesh thickness. Each factor is tested at a J_g of 0.98 cm s^{-1} , 1.31 cm s^{-1} and 1.64 cm s^{-1} for a total of 45 treatment combinations.

MESH HOLE-SIZE (mm)	THREE FACTOR FACTORIAL DESIGN MATRIX								
	Mesh thickness (mm), at each level of J_g								
	20			30			40		
	0.98 cm s^{-1}	1.31 cm s^{-1}	1.64 cm s^{-1}	0.98 cm s^{-1}	1.31 cm s^{-1}	1.64 cm s^{-1}	0.98 cm s^{-1}	1.31 cm s^{-1}	1.64 cm s^{-1}
10	M1x2	M1x2	M1x2	M1x3	M1x3	M1x3	M1x4	M1x4	M1x4
20	M2x2	M2x2	M2x2	M2x3	M2x3	M2x3	M2x4	M2x4	M2x4
30	M3x2	M3x2	M3x2	M3x3	M3x3	M3x3	M3x4	M3x4	M3x4
40	M4x2	M4x2	M4x2	M4x3	M4x3	M4x3	M4x4	M4x4	M4x4
50	M5x2	M5x2	M5x2	M5x3	M5x3	M5x3	M5x4	M5x4	M5x4

3.6.2 Statistical analysis

Once the experimental trial has been concluded, the relevant data from each experiment was entered into the ANOVA table. An analysis of the data was then undertaken in the statistical package Minitab 17 (Minitab, 2015).

The ANOVA partitioned the variance into its components and made comparisons between them. It considered whether there is significance between the variance of the means for the effect of mesh hole-size, thickness and J_g on air recovery, liquid and solids flowrates, as well as the interactions between them, using the F-test. The output value,

the P-value, is a measure of risk. If small, it suggests the variance in the dataset is not random but is the result of changing one or more of the factors from one level to another. If so, the factor is affecting performance to a level of statistical significance. A P-value less than 0.05 corresponds to a 95 % confidence level that in fact the interactions are not random but a function of the changes to the levels of the factors being tested.

Minitab 17 not only allows for this analysis of variance, but also allows plots of main effects (the mean effect of mesh hole-size, thickness and Jg) and plots of interactions between two of the factors. The ANOVA is not capable of determining if there is a statistical significance associated between performance indicators for each design. This is determined in two ways.

The data in the ANOVA can be used to compare one treatment with the remainder in the factorial. Dunnett's method is used create confidence intervals for differences between the mean of each factor level and the mean of a selected treatment. If an interval contains zero, then there is no significant difference between the two means under comparison (Minitab, 2015). In order to compare with the unmodified base case, a one-way t-test to compare sample means is undertaken. This determines if there is a statistically significant improvement in the mean of the treatment against the unmodified base case.

3.7 Retrofit designs

The factorial plan requires a range of meshes to be designed and 3D printed. This design and production process is discussed in this sub-section.

3.7.1 Mesh design and 3D printing

The meshes were designed in Sketch Up, a 3D CAD software package. The meshes follow some key design principles. The total surface free area available from each mesh design size is the same. As the size of the mesh hole-size increases, the total open area remains the same, and therefore the wall thickness of the mesh also increase to accommodate this. The mesh hole-size was based on the longest diagonal of the polygon. The pattern of the mesh was centred on the middle of the mesh, and therefore the arrangement and shape of holes at the edge varied, depending on the configuration under investigation. Table 3.3 and Figure 3.13 summarise the different hexagonal mesh configurations. The meshes are shown in Figure 3.13. The top of the mesh was positioned

40 mm below the lip of the cell, at the pulp-froth interface. The meshes are either 20, 30 or 40 mm in thickness.

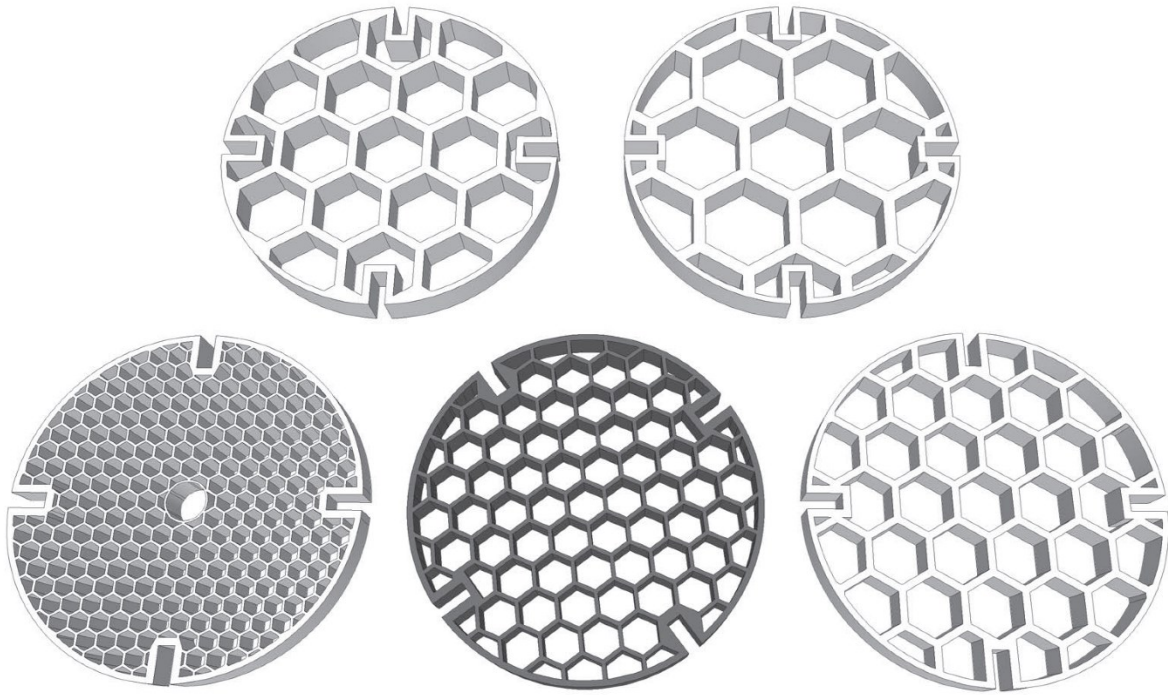


Figure 3.13 - The five hexagonal meshes designed for testing in the flotation cell. Meshes are 180 mm in diameter. Top from left to right, 40 mm and 50 mm hole-size, bottom from left to right 10 mm 20 mm and 30 mm hole-sizes (own work).

Once the mesh had been designed, it was exported as a .stl file. The file was then imported into the proprietary software supplied for the 3D printer. The 3D printer used was an Objet30 Pro. The printer built up the object in layers with a 28 μm thickness of a range of ABS plastics. The print time varied but can be up to 24 hours. The printer is accurate to 100 μm thickness, and has a build tray size of 300 x 200 x 150 mm, well within the requirements for the meshes required for the flotation cell. The cell has a diameter of 180 mm and the mesh thickness varied from 20 to 40 mm. Once printed, the meshes were blasted clean with a high-pressure water jet and cleaned in 5 L of a 2 M sodium hydroxide solution to remove any remaining impurities on the surface.

3.7.2 Mesh implementation

The meshes were designed to be easily retrofitted to the cell. In order to fit a mesh, the impeller shaft and gearbox was disconnected from the motor and frame, and removed. The impeller was then removed from the end of the shaft, and the mesh was then slotted onto the impeller shaft. The impeller was then reattached to the shaft.

The whole assembly was then placed back into the flotation cell and the gearbox and shaft are reattached to the motor and frame. The mesh was then placed on top, or slotted onto the baffles, depending on the configuration being tested. The meshes were held in place with a small amount of hot glue on the baffles.

3.8 Positron Emission Particle Tracking (PEPT)

Positron Emission Particle Tracking (PEPT) allows us to follow particle paths within opaque systems through tracing of an irradiated particle. This allows us insights into how the motion and behaviour of hydrophobic and hydrophilic particles are affected by changes to different experimental parameters such as air rate, impeller speed and cell design. In this thesis, the effect of retrofit meshes were investigated using PEPT on tracer behaviour.

3.8.1 PEPT tracer production

A detailed description of tracer production for these experiments can be found in Cole et al. (2014). For each experiment, a tracer was prepared by staff from iThemba LABS in Cape Town. Two types of tracer were manufactured, hydrophobic or hydrophilic, depending on experimental requirements. The hydrophobic tracer replicated the mineral behaviour in a flotation system, and the hydrophilic tracer, the gangue behaviour. The tracer contained a Purolite NRW100 ion exchange resin core, approximately 430-575 μm in size. Several cores were shaken with 0.2 mL of deionized water containing approximately 8 mCi of ^{68}Ga activity for one hour (Cole et al., 2014). This successfully labelled the tracer.

Following radiolabelling, to produce a hydrophobic tracer, the resin was dipped in a rapidly curing epoxy resin. It was then rolled in silanised ballotini and allowed to set. The tracer was then examined to ensure it was coated before being transported to the experimental system. The radiolabelled resin core was used without modification for the

hydrophilic experiments, being hydrophilic by nature (Cole et al., 2014). A tracer with an activity of 1 to 2 mCi was desirable.

3.8.2 PEPT tracer utilization and post experimental procedures

Following production, the tracers were inserted into the flotation experiment as previously described. The tracers were used for up to 4 hours depending on their initial and final activities.

As the hydrophilic tracer was uncoated, it leached activity into the experiment. This also occurred with the hydrophobic tracer but to a lesser extent. As a result, the experimental system, and in particular, the liquids and solid in the experiment were mildly radioactive once experimentation has ceased. The tracer was first extracted from the experiment by pumping it through the recycle and out through a tap. The tracer was then located, placed in a glass vial and put behind lead brick shielding. The remaining pulp was pumped out and placed in a beaker overnight to allow the activity to dissipate. The tracer, once inert, was photographed to check for fragmentation or damage.

3.8.3 PEPT data collection and analysis

The tracers used in the experiment were position emitters as previously discussed in Chapter 2 section 6. As the radionuclide decayed, it emitted positrons. The annihilation of the positron with an electron produced a pair of near back-to-back γ -rays, which were detected by the PET camera. The data capture system collected 10 minute blocks that were then processed to provide the raw positional data from the system. The data was recorded at a rate of 1000 counts per second.

Firstly, a triangulation algorithm based on that used by Parker et al. (1993) was used to locate the position of the tracer for each annihilation event. It is based on the premise that for a given number of events, N , all the lines of response (LORs), which are the result of the near back-to-back γ -ray emissions intersect at the exact point of the tracer (Parker et al., 1993; Cole et al., 2014). In the case of the experiments undertaken as part of this work, the value of N was set to 100. In reality, the LORs do not intersect, and so the mean position was the point in space between the LORs which minimizes the distance to each (Parker et al., 1993; Cole et al., 2014). During this process, anomalous results caused by Compton scatter and other events such as background gamma rays were also removed.

This is by reducing the fraction of events to minimise the effect of noise on the dataset. This fraction, f , was set to 30 % of the recorded locations, and post processing, any locations outside the region of study, or 7 mm or greater distance from the mean location were removed from the dataset (Cole et al., 2014). This process was undertaken in MATLAB, using in-house scripts compiled by Dr Kathryn Cole and Angus Morrison.

Secondly, an in house developed smoothing kernel, written in C+ by Dr Steven Neethling, in-house at Imperial was applied to the data. The kernel is a statistical technique to smooth out the position of the tracer over a chosen time frame, 100 ms. The raw time indexed data was then read in by a MATLAB script, which can display the data points in either the x, y or z orientation, or in 3 dimensions. The data was centred into the pre-defined field of view of the flotation cell as set out in MATLAB. This can be observed in Figure 3.14.

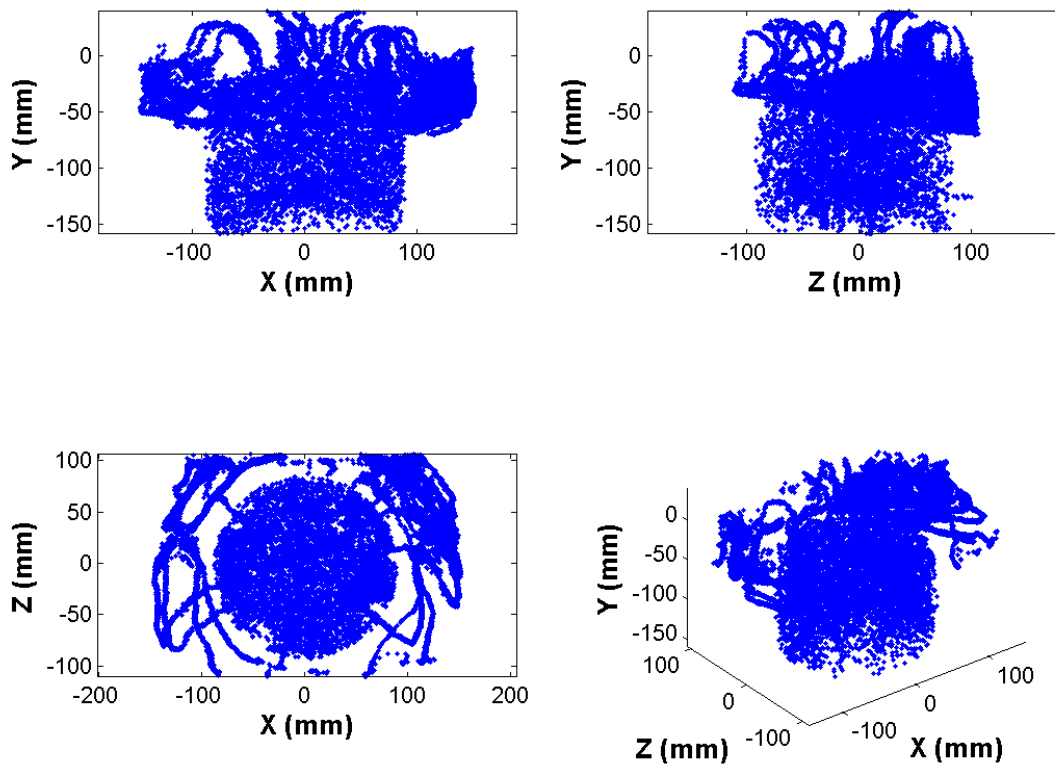


Figure 3.14 - Raw hydrophobic tracer data in the y, x and z dimensions, and in a 3D block (own data)

Raw tracer location data could then be plotted, or manipulated in MATLAB in order to output tracer speed, standard deviation of speed and tracer occupancy in both vertical and horizontal planes through the flotation cell, with data averaged onto a 2D plane for both visual and numerical comparison. Comparisons are carried out within 10 mm blocks. Speed is calculated by dividing the distance between 3 events, by the time taken for the tracer to travel the total distance, with the standard deviation of speed determined using the number of speed events calculated within the block. Occupancy is the number of times the tracer was located within the block. Videos of the tracer motions could also be produced to visualise their behaviour in the pulp and froth phases.

The standard deviation of speed of the tracers was taken to be indicative of turbulence. This follows from Abrahamson (1975), who first took the mean squared velocity deviation as a measure of turbulence experienced by particles in the size range of flotation in highly turbulent suspensions. Pyke et al. (2003) built upon this work to derive the number of collision events depending upon particle size.

3.9 Summary

During the course of this PhD, a 4 L bench-scale cylindrical recycling flotation system was developed. An experimental rig was also been constructed, to which various apparatus can be attached and the flotation cell contained within. A single species particle-stabilised froth was created making use of silica ballotini, a frother (MIBC) and a collector (TTAB). The experimental system was capable of operating over several hours. The effect of changes to the particle size distribution on froth behaviour could therefore be investigated. The system recorded measurements of the froth depth and overflowing velocity in order to determine the air recovery, and physical samples of the froth concentrate could be taken for comparison. Through changing air rates, PAR could be determined for particle-stabilised froths, and the associated recovery of both liquid and solid determined.

The experimental rig is modular, allowing for replacement of components and the addition of design modifications such as the horizontal mesh. The mesh can be 3D printed or manufactured in order to modify the system. These meshes can be added and removed between experiments, and the measurement systems can allow us to determine the effects of the mesh on both air recovery and flotation performance.

Different operating conditions, as well as modifications to the flotation cell design lead to changes in solid, liquid and gas behaviours in the flotation cell. The use of PEPT, Positron Emission Particle Tracking, allows us to insert radioactive tracers into the flotation cell. The tracers can mimic the behaviour of both mineral and gangue, acting as hydrophobic and hydrophilic materials. By changing the operating parameter or cell design, the motion and position of the tracers can be determined and analysed for comparison. This provides an insight into how recovery of particles from the system is being affected.

Chapter 4

Air recovery: the link to particle size

4.1 Introduction

Air recovery, the fraction of air entering a flotation cell that overflows the cell lip, is linked to flotation performance. It has been shown through industrial test work that operating flotation cells at air rates that yield the Peak Air Recovery (PAR) results in high mineral recovery (Hadler and Cilliers, 2009). For operating parameters over which flotation plants have little control, such as particle size, investigating the effect on the position of PAR, and the subsequent effect on flotation performance, proves more challenging.

In this Chapter, the effect of varying the particle size distribution on the operating performance and air recovery of the flotation system described in Chapter 3 is discussed. Air recovery is measured, and samples of the overflowing concentrate are taken in order to determine the operating performance of each condition, including the particle size distribution of the recovered concentrate.

4.2 The effect of particle size on the air recovery

The effect of the superficial gas velocity on air recovery, as a function of the different particle size distributions, are shown in Figure 4.1. Errors are given as 95 % confidence intervals. Each set is repeated three times and the mean values are presented.

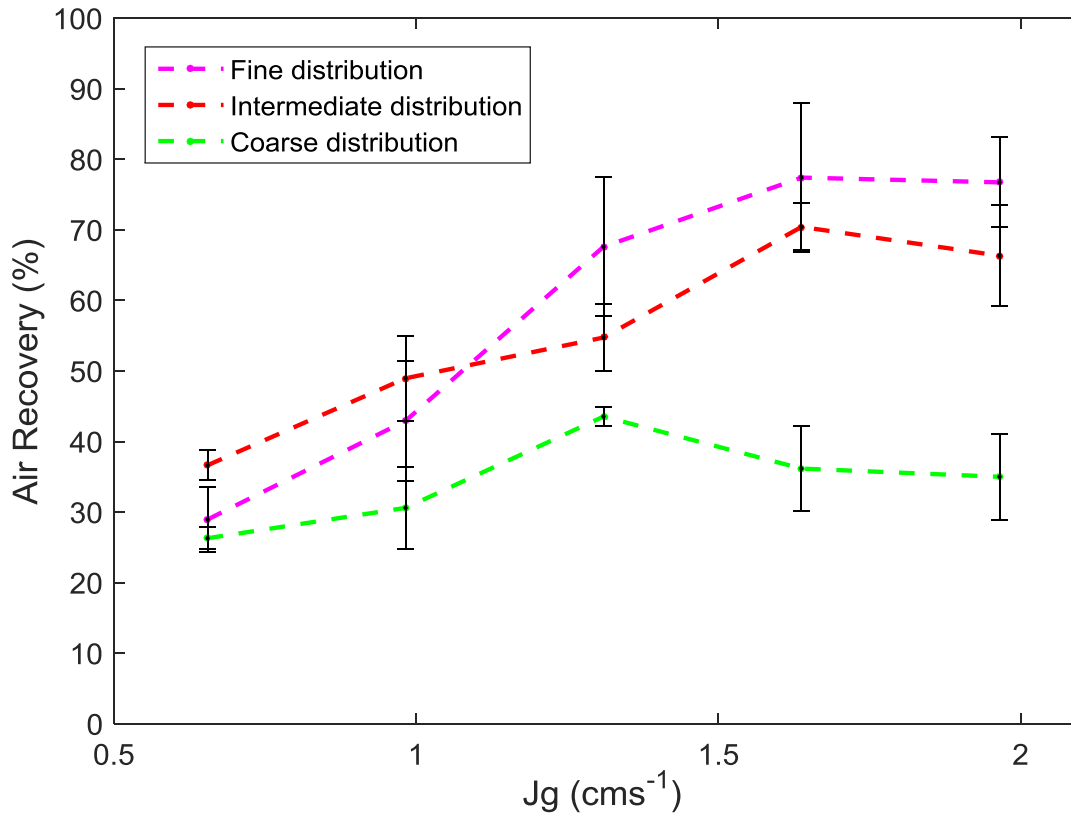


Figure 4.1 - Air recovery as a function of superficial gas velocity, for the three particle size distributions tested.

Inspection of Figure 4.1 revealed that in general, the finer the particle size distribution, the greater the air recovery, reaching a maximum of 78 %. The peak in air recovery appeared to shift to the right (an increase in the superficial gas velocity) with a decrease in the particle size distribution. The coarse distribution, as shown in green, showed an increase in air recovery from a J_g of 0.66 cms^{-1} through to a peak at a J_g of 1.31 cms^{-1} , before decreasing towards a J_g of 1.97 cms^{-1} . All the air recovery values fall below 50 % for the coarse system. The confidence intervals overlap in many cases for the intermediate and fine distributions, and so the individual data points are shown in Figure 4.2 for comparison.

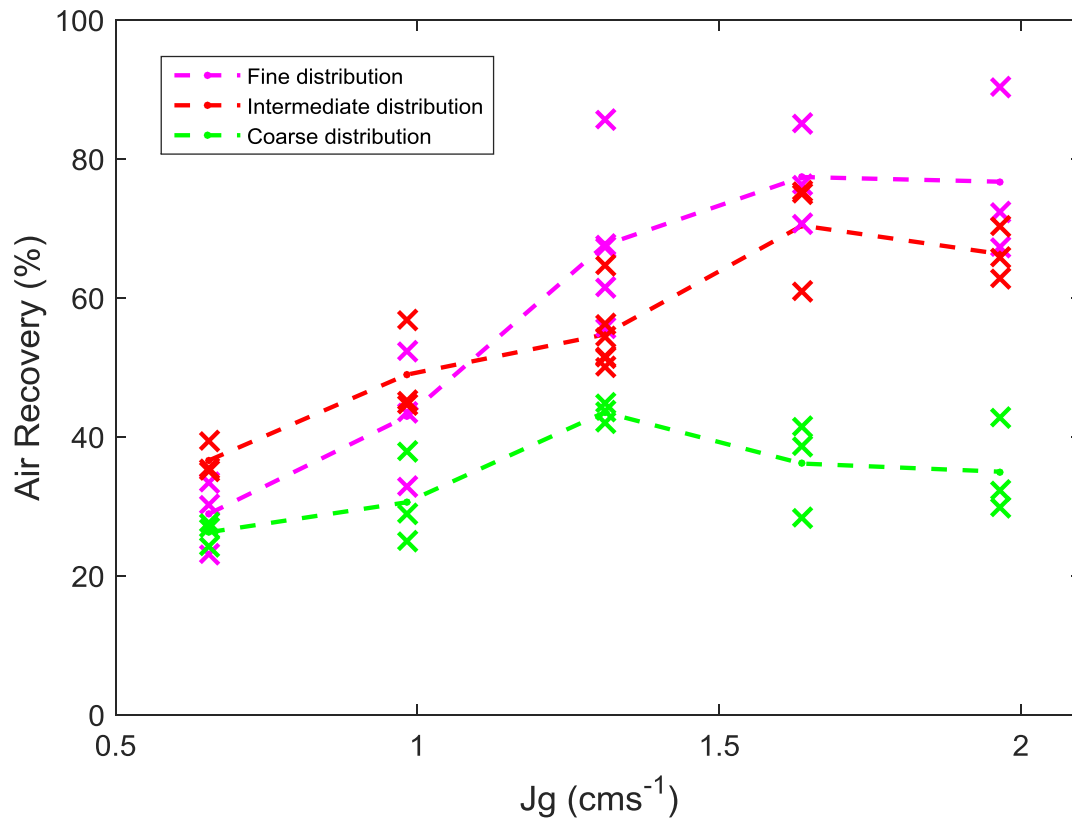


Figure 4.2 - Air recovery as a function of superficial gas velocity, for the three particle size distributions tested. Individual data points are displayed

Considering the intermediate distribution, the highest air recovery occurred at a Jg of 1.64 cms⁻¹. Air recoveries began at approximately 35 % and air recoveries to a value of approximately 66 % at a Jg of 1.64 cms⁻¹. Air recovery then falls marginally at a Jg of 1.97 cms⁻¹. The air recovery values are consistently higher than those displayed by the coarse particle distribution.

The fine distribution displays air recoveries initially smaller than the intermediate system. Air recovery at a Jg of 0.66 cms⁻¹ is just over 30 %. It then increases towards a Jg of 1.97 cms⁻¹. Air recovery exceeds the intermediate system at a Jg of 1.31 cms⁻¹, where air recovery increased above 60 %, before approaching 80 % at a Jg of 1.64 cms⁻¹, and then 78 % at a Jg of 1.97 cms⁻¹. The peak in air recovery was at a higher value of 1.97 cms⁻¹.

Observing the individual data points as presented in Figure 4.2, there was considerable overlap of the values for the intermediate and fine distribution at superficial gas velocities of 0.98 cms⁻¹, 1.64 cms⁻¹ and 1.97 cms⁻¹. The values for the fine distribution, particularly

at the higher values of J_g were marginally greater, but it is not conclusive from the distribution of values as shown in Figure 4.2.

As can be seen, Figure 4.1 and Figure 4.2 provided results for three size distributions, and not the four outlined in the methods. The coarsest distribution was not shown because it was incapable of forming a sustained particle-stabilised overflowing froth across the range of superficial gas velocities tested. This was a very interesting observation given that the feed p_{50} varies by only approximately 40 μm across all four distributions. This immediately implies that the experimental system is sensitive to particle size. From the data presented, there appeared to be a clear link between particle size and air recovery. The data shows that coarse particles are associated with lower air recoveries. This suggests that coarser particles require lower air rates to achieve optimal stability. As particle size decreases, air recovery increases. The trends of the fine and intermediate fractions are very similar, although the magnitude of the air recovery of the fine particle set system is greater at higher air rates, but there is no statistical significance between the two datasets for a J_g of 1.64 cm s^{-1} and 1.97 cm s^{-1} , as can be seen from the overlapping means and confidence intervals. The peak in air recovery also appears to shift to higher air rates with a reduction in particle size. This suggests that fine particles result in more stable froths, and therefore higher air recoveries. Fine particles have been previously noted by Szatkowski and Freyberger (1985) to stabilize the froth phase, but the link to higher air recoveries has yet been made.

4.3 The effect of particle size on solid and liquid flowrates

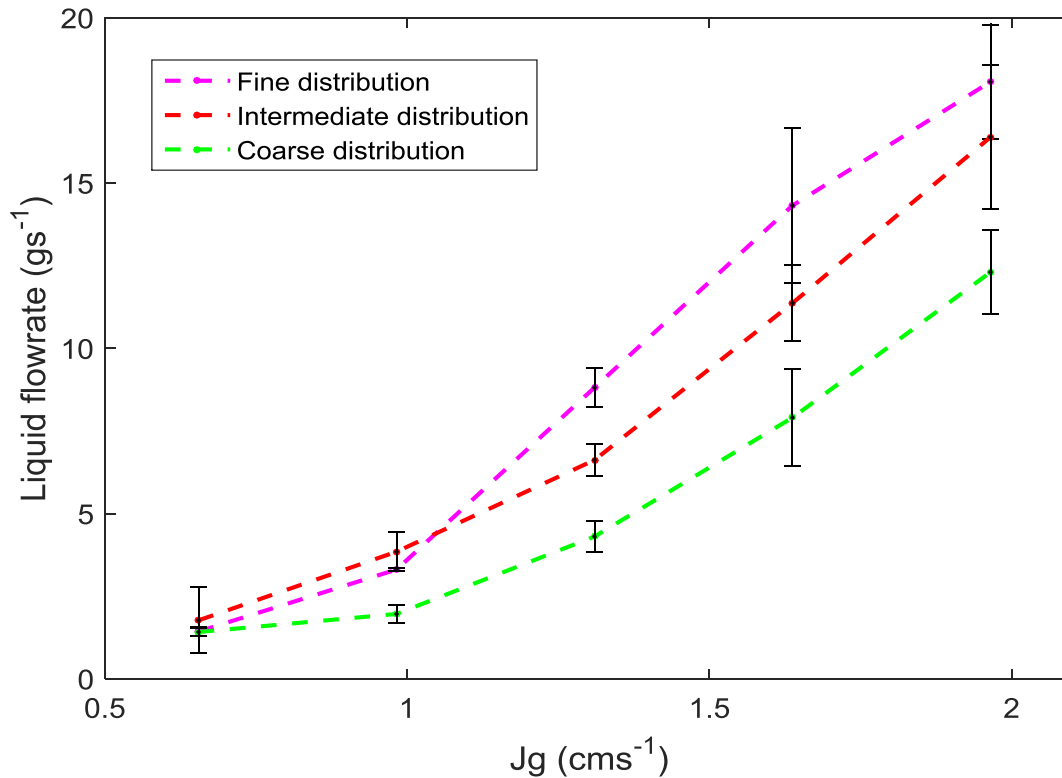


Figure 4.3 - Liquid flowrate as a function of superficial gas velocity, for the three particle size distributions tested. Errors are given as 95 % confidence intervals.

Figure 4.3 considers the liquid flowrate to the concentrate as a function of the superficial gas velocity, for each particle size distribution. The finest distribution has the highest liquid flowrates and the coarsest the lowest, with the difference in flowrates becoming more pronounced at higher air rates. This corresponds with previous findings that higher air rates result in higher liquid content which in turn is associated with higher recovery of fine particles, where entrainment is a contributor in particle recovery (Engelbrecht and Woodburn 1975; Neethling and Cilliers, 2009). As can be seen in Figure 4.3, for a J_g of 0.66 cms^{-1} , the liquid flowrates were very similar for all three particle size distributions. As the gas velocity was increased to 0.98 cms^{-1} , the intermediate and fine distributions remained similar, but increased significantly relative to the coarse system. At a J_g of 1.31 cms^{-1} , all three particle size distributions began to diverge, with the fine distribution being associated with a higher liquid flowrate than the intermediate system; liquid flowrates were effectively doubled for the fine system relative to the coarse, with the intermediate lying between the two. This trend generally continued through to the highest J_g of 1.97

cms^{-1} , where liquid flowrates were significantly greater for the fine distribution than the coarse distribution.

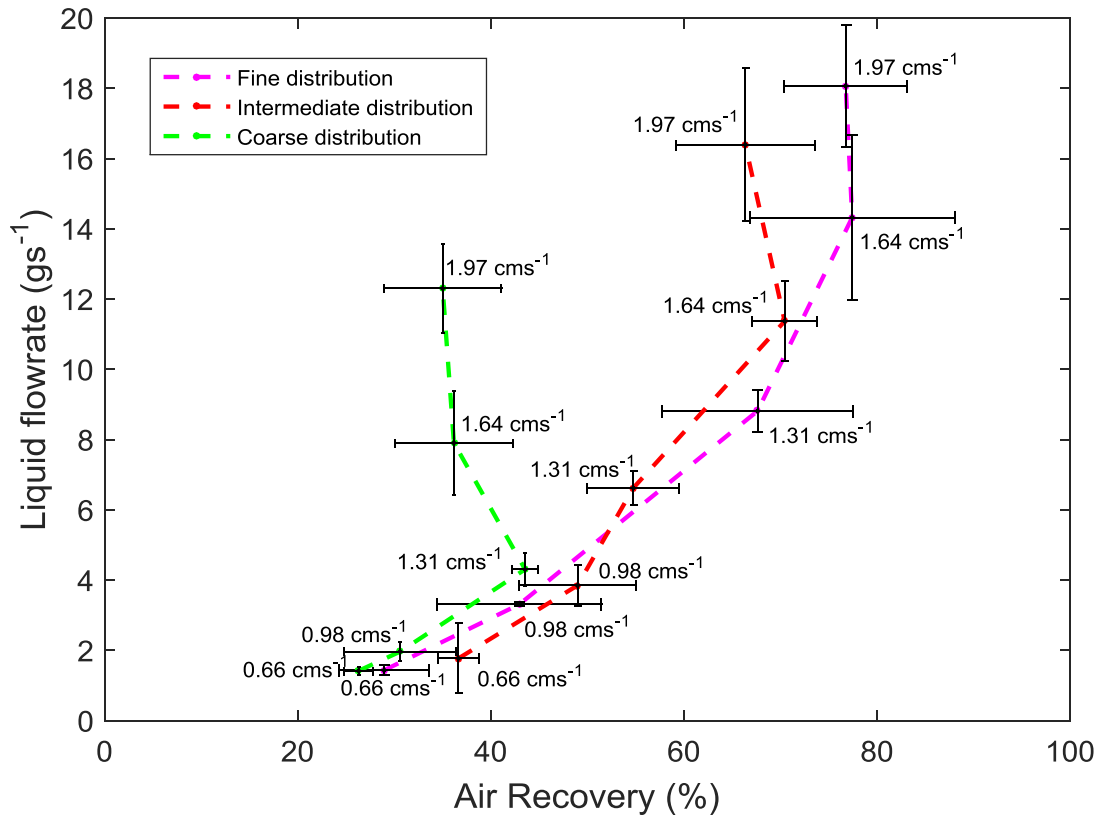


Figure 4.4 - Liquid flowrate as a function of air recovery for the three particle size distributions tested. Errors are given as 95 % confidence intervals

The differences in particle size distributions, having an effect on the liquid recovered to the concentrate are further highlighted in Figure 4.4. This variance in liquid content affects the structure of the froth phase, its stability and ultimately has an effect on the air recovery. Figure 4.4 links high air recovery to high liquid recovery. High liquid content values in the froth phase can influence the stability of the froth phase, reducing the stabilizing effect of the particles. Liquid recoveries are not dependent on air recovery when it exceeds 50 %. For the intermediate and fine systems, the air recovery exceeds 50 % at and above a J_g of 1.31 cms^{-1} , and so air recovery is not necessarily linked to liquid quantities at these values.

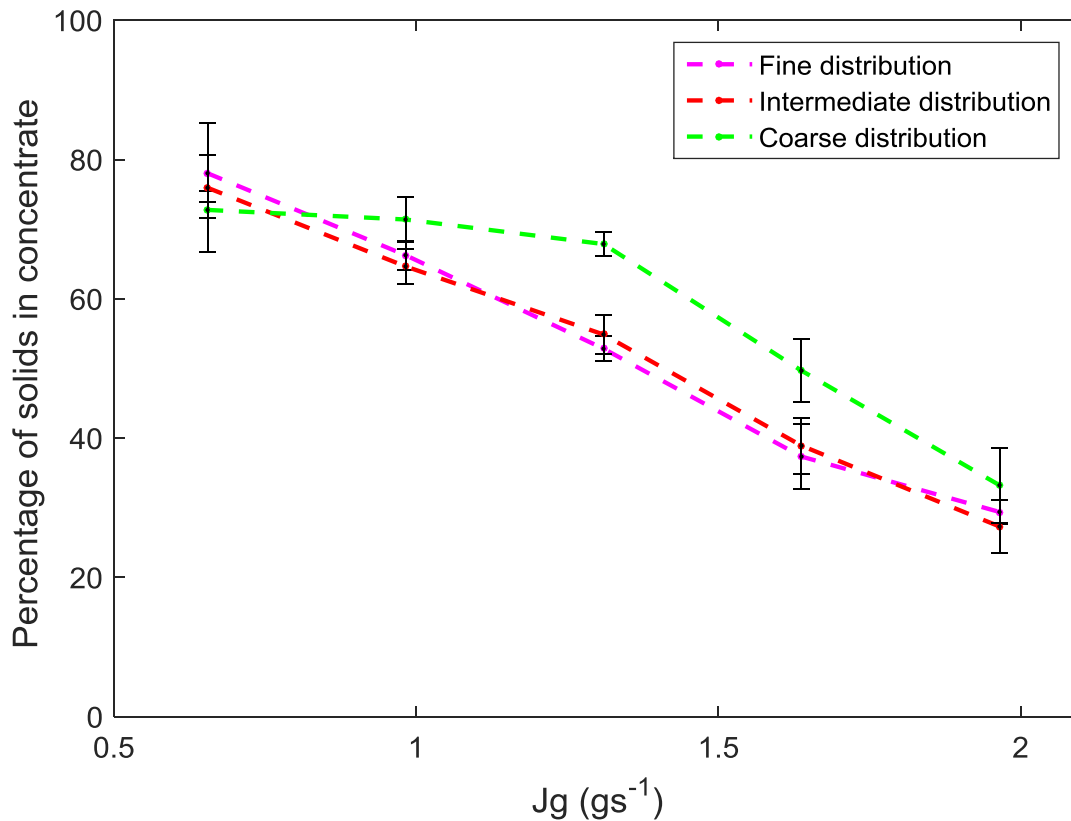


Figure 4.5 - Percentage of solids in concentrate by mass as a function of superficial gas velocity, for all three particle size distributions tested. Errors are given as 95 % confidence intervals.

Figure 4.5 considers the proportion of solids by mass in the concentrate for each superficial gas velocity tested. At the lowest value of J_g , solids content by mass was between approximately 70-80 %. As J_g was increased to 0.98 cm s^{-1} , there was little change in the liquid content of the coarse particle froth. However, the fine and intermediate froths rapidly increased in liquid content, falling to 70 % by mass solid and then further falling at a J_g of 1.31 cm s^{-1} , with the fine system falling to approximately 50 % by mass solid and the intermediate system falling to the same proportion. The coarse system remained at approximately 70 % air recovery. An increase in J_g to 1.64 cm s^{-1} results in the intermediate and fine systems falling to 35 % by mass solid, while the coarse distribution remains particle stabilized, with a solids content of approximately 50 % by mass. At the highest J_g of 1.97 cm s^{-1} , the solids content by mass of all distributions converged on a value of approximately 30 %. The coarse distribution retained the lowest liquid content and the fine system the highest.

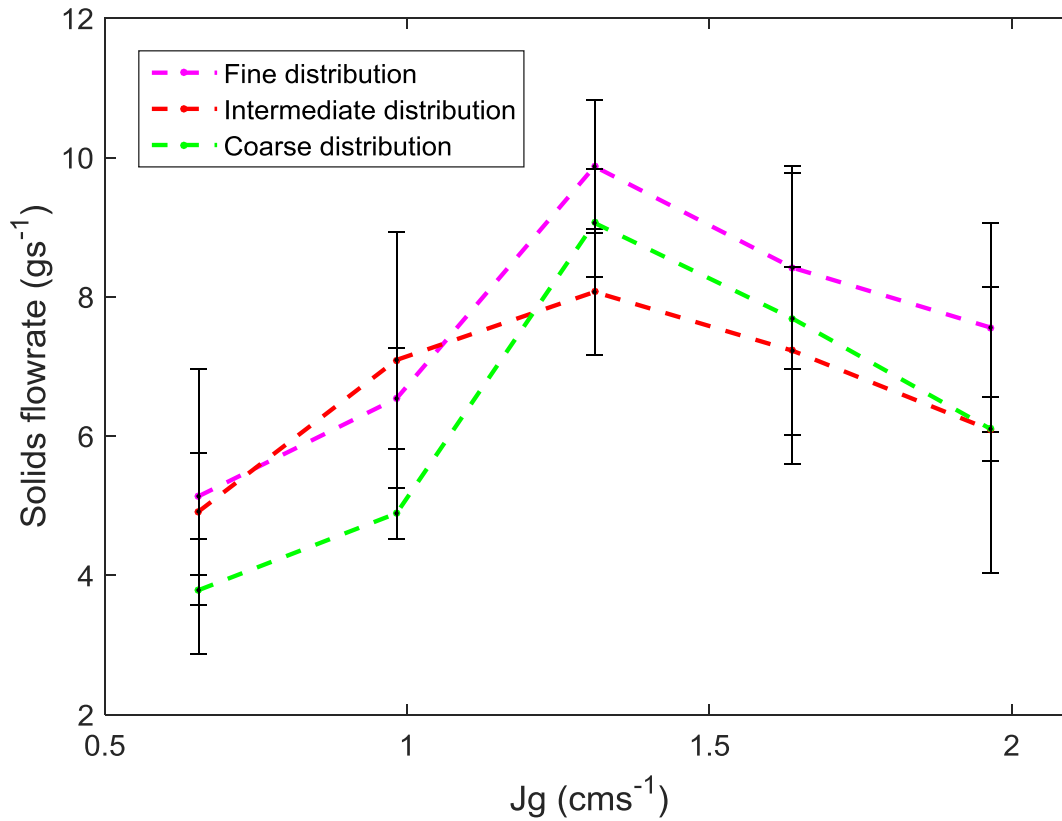


Figure 4.6 - Solids flowrate as a function of superficial gas velocity, for all three size distributions tested. Errors are given as 95 % confidence intervals.

Figure 4.6 considers the solids flowrate as a function of the superficial gas velocity, with respect to each particle size distribution. Observations suggest that the fine particle size distribution was associated with the highest flowrate of solids to the concentrate, and the coarse distribution the lowest solids flowrate. For all three distributions, there was an increase in solids flowrate, from a J_g of 0.66 cms^{-1} to a peak in solids flowrate at a J_g of 1.31 cms^{-1} . There was then a decrease in the solids flowrates for all distributions through to a J_g of 1.97 cms^{-1} . The confidence intervals are large for several of the datasets and so the individual data points are presented in Figure 4.7.

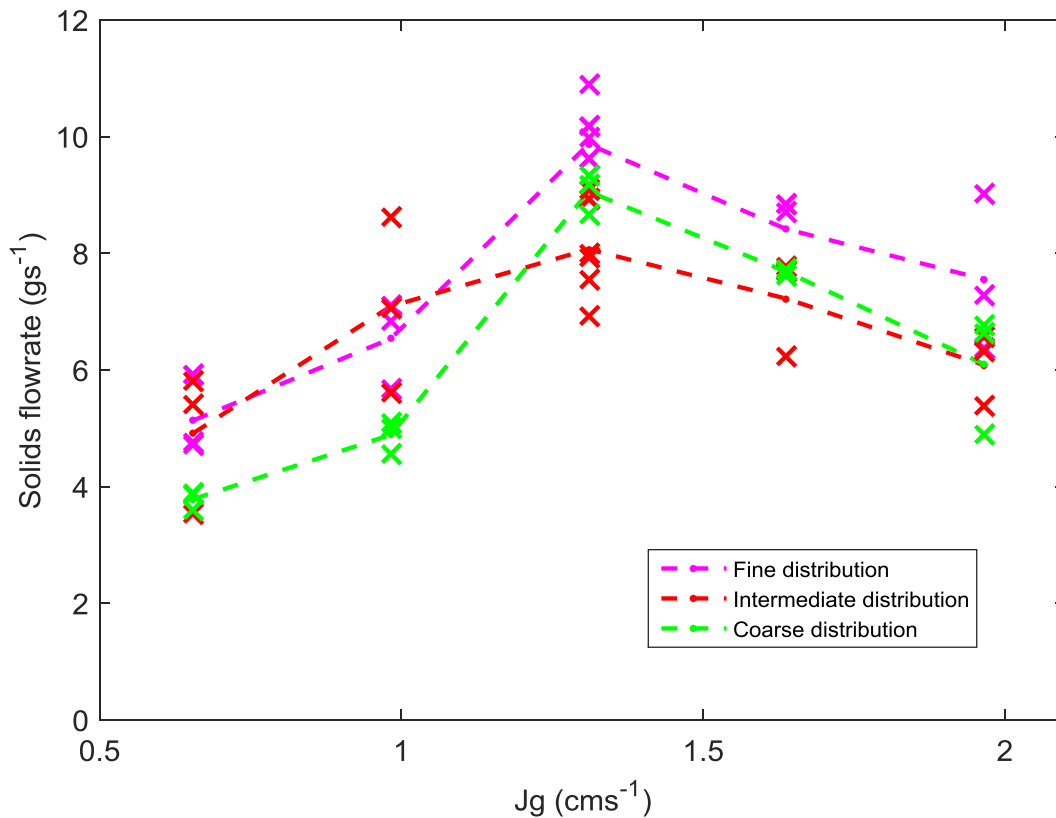


Figure 4.7 - Solids flowrate as a function of superficial gas velocity, for all three size distributions tested. Errors are given as 95 % confidence intervals.

As can be seen in Figure 4.7, the data points are tightly constrained for the coarse particle distribution. It also appears that at J_g 's above 1.31 cms^{-1} , the fine distribution had a higher solids flowrate than the intermediate distribution. The intermediate distribution had the lowest solids flowrate at a J_g of 1.31 cms^{-1} , but at higher J_g 's it is indistinguishable from the coarse distribution. These observations are generally aligned with those given for Figure 4.6, with the intermediate distribution having performed poorly at higher values of J_g , despite having a finer feed distribution than the coarse distribution. The fine distribution results in the highest overall solids flowrates across all values of J_g .

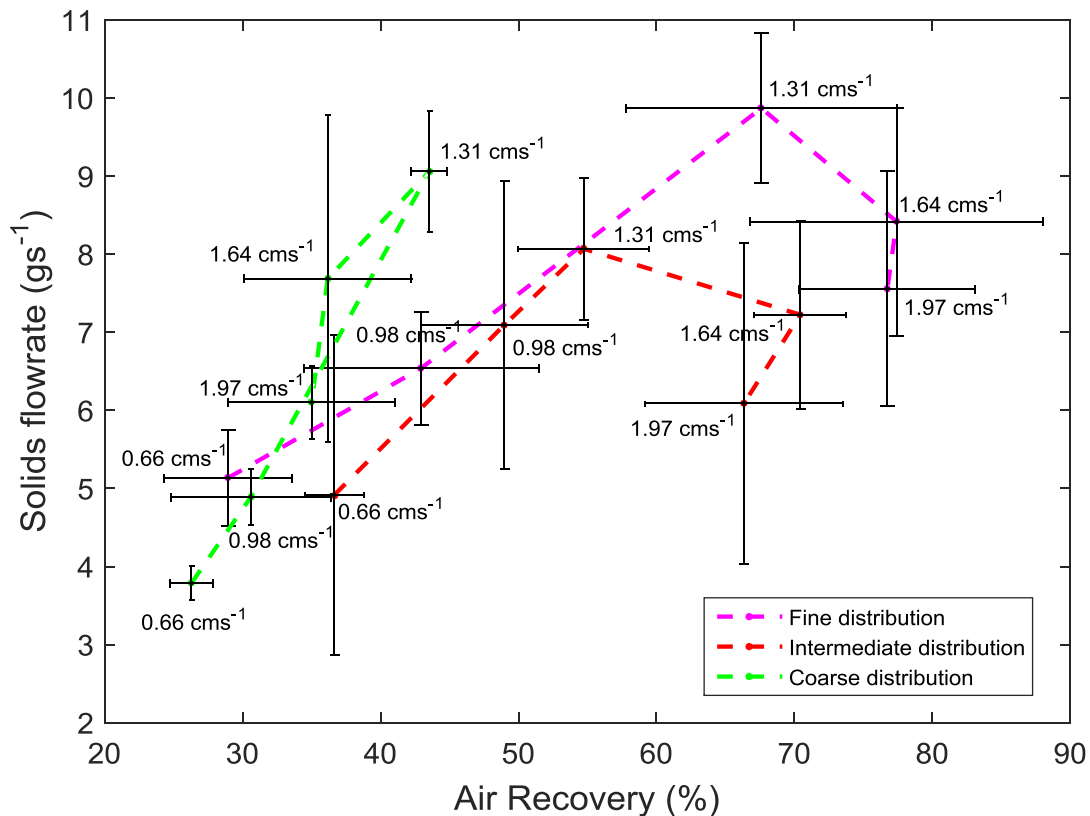


Figure 4.8 - Solids flowrate as a function of air recovery for the three particle size distributions tested. Errors are given as 95 % confidence intervals

Figure 4.8 considers solids flowrate as a function of air recovery. It is clear that in each case, solids recovery peaks at a J_g of 1.31 cms^{-1} . However, the profiles for the coarse distribution versus the intermediate and fine distributions are different. The Coarse distribution increases in air recovery with a larger gradient to the peak in solids flowrate which exists at the peak in air recovery, before decreasing at a similar rate in both air recovery and solids flowrate. Air recoveries remain below 50 % for this distribution.

The air recoveries of the intermediate and fine distributions continue to increase beyond the peak in solids flowrate. When air recovery is below 50 %, the peak in air recovery is associated with a peak in solids flowrate. Solid and liquid flowrates are not dependent on the air recovery above this value. As shown in Figure 4.8, this observation can be made for the intermediate and fine distributions, and so the peak in solids flowrate is not necessarily associated with the peak in air recovery in these cases.

The results suggest there is a relationship between particle size, liquid content and air recovery, and that finer particles are associated with high liquid recoveries. The liquid

flowrate dominates in the fine and intermediate particle systems and is a significant contributor to froth stability at higher air rates. For the coarse particle distribution, air recoveries never exceed 50 %, and so it would be expected that there is a link between peak solids flowrate and the peak in air recovery for this distribution.

As shown in Figure 4.1, PAR exists at a J_g of 1.31 cm s^{-1} . It would be expected that the peak in the solids flowrate is at the same J_g . Inspecting Figure 4.6 shows that this peak exists and correlates with the peak in air recovery as shown in Figure 4.8. As set out, this distribution satisfies all the parameters to be considered a particle stabilized froth at this particular superficial gas velocity, as well as the subsequent velocity of 1.64 cm s^{-1} , where there is a reduction in both air recovery and the solids flowrate. This reinforces previously seen matches in the peak in air recovery and the peak in solids flowrate for industrial systems (Hadler and Cilliers, 2009).

The data suggests a very strong relationship between particle size, solids content and liquid content in the froth phase. By decreasing the particle size, the liquid and solids content of the froth is adversely affected, so much so that the froth switches from one that is particle stabilized to one with a large contribution from the liquid content, under otherwise similar operating conditions. This feeds back into increased air recovery measurements. This highlights the benefit of combining froth measurements, such as air recovery, with physical measurements that allows for a more complete interpretation of the data. Particle size has a significant, notable and variable effect upon the various parameters of the flotation system.

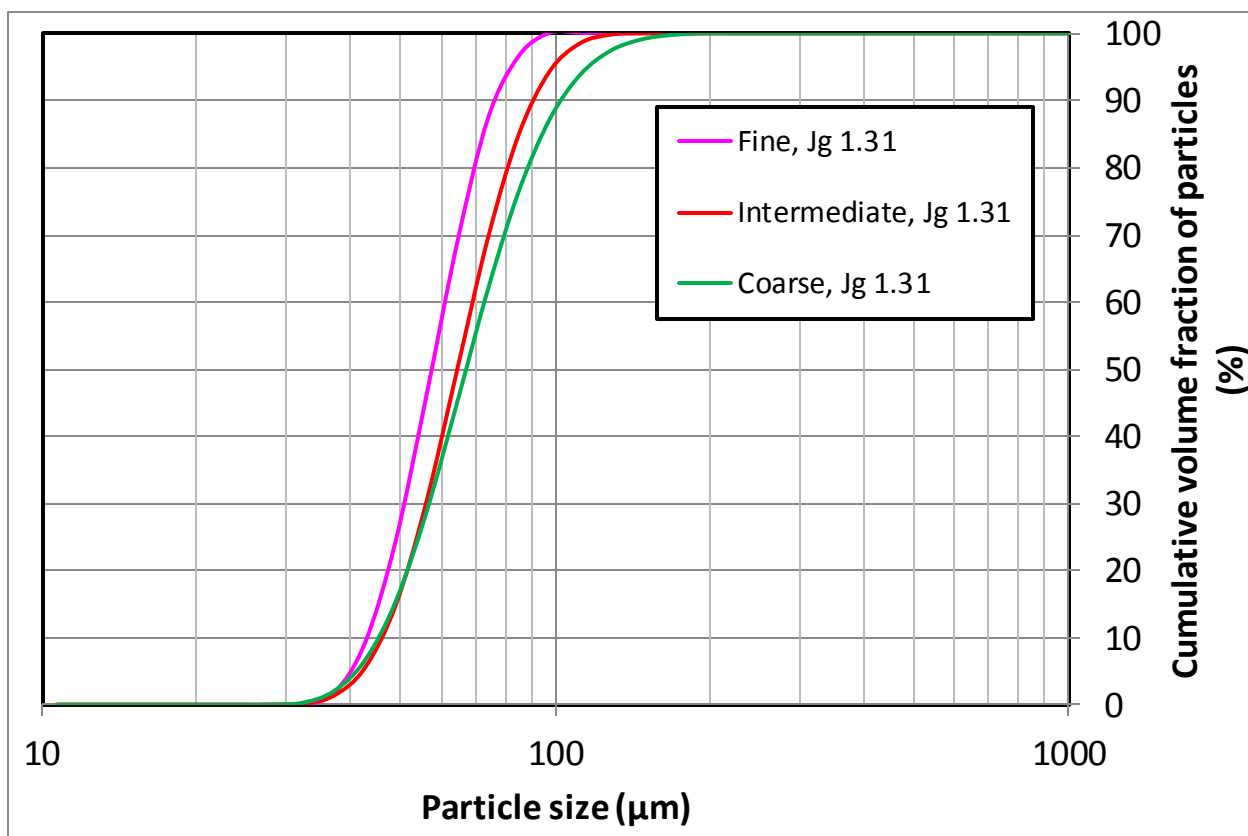


Figure 4.9 - Particle size distribution of the concentrate at a J_g of 1.31 cms^{-1} .

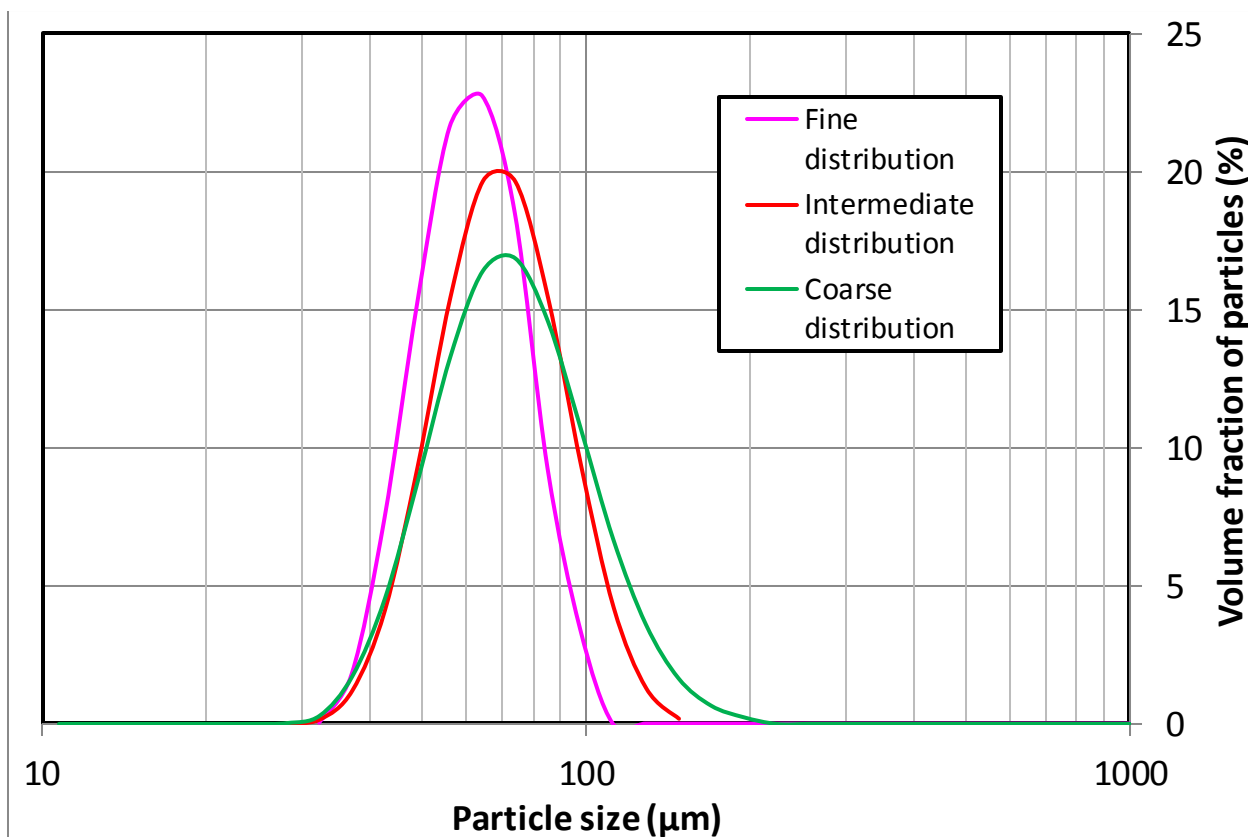


Figure 4.10 - Fractional particle size distribution of the concentrate at a J_g of 1.31 cms^{-1} .

Figure 4.9 and Figure 4.10 consider the particle size distributions of the concentrate of all three distributions tested, at a J_g of 1.31 cms^{-1} . It can be observed that the fine particle size has the finest distribution in both the feed (Figure 3.6) and the concentrate. The fine and intermediate concentrate distributions show a difference of approximately $2 \text{ }\mu\text{m}$ at p_{50} with the feed distribution. The coarse distribution results in the concentrate with the largest particle size, and the intermediate and coarse particle size distributions are similar in their distributions. The p_{50} of the distribution has however dropped approximately $28 \text{ }\mu\text{m}$.

Figure 4.5 indicates the proportion of liquid to solid is approximately the same for both the intermediate and fine systems. The intermediate system however, considering Figure 4.6, is recovering less solids than the coarse at a J_g of 1.31 cms^{-1} and higher. With a smaller proportion of coarse particles recoverable to the concentrate while maintaining a similar distribution to the coarse, as shown in Figure 4.10, and a high liquid flowrate as observed in Figure 4.3, higher air recoveries could potentially result, as seen in Figure 4.1, for the intermediate system relative to the fines. As a consequence of a low coarse solids content in the feed, Solids flowrate to the concentrate, as observed in Figure 4.6, can reduce relative to the coarse distribution at PAR and higher values of J_g . The coarse distribution has a lower air recovery and a lower liquid flowrate than either the intermediate and fine distributions. The coarse distribution retains a higher solids flowrate relative to the intermediate distribution at a J_g of 1.31 cms^{-1} and higher.

Particle size affects all sub-processes occurring in flotation, including collision and detachment in the pulp phase, and entrainment and film stability in the froth phase. For example, as particle size decreases, the probability of collision with and attachment to bubbles decreases, but there are an increased number of potential events (Luttrell and Yoon, 1992) but conversely, the probability of detachment is higher for coarser particles (Crawford and Ralston, 1988). Coarse particles have a tendency to destabilize the froth (Moudgil, 1992). Fine particles have been shown to stabilize the froth (Aktas et al., 2008) and are more frequently entrained into the froth phase (Neethling and Cilliers, 2009), and both may have a significant role in the increased recovery and stability of the froth phase. It is worth bearing in mind the small range of particle sizes under investigation in this experimental system, the coarse particle distribution is not coarse in terms of true flotation systems.

Other effects of changing the particle size include changing the total available surface area for a given mass of solid. There may also be fluctuations in the proportion of collector remaining in the pulp relative to the surface of the solid. This will further affect the stability of the froth. The interaction of these varying parameters is extremely difficult to quantify. Small changes in experimental temperature will also affect the rate kinetics of the various reactions taking place in the system (Klimpel, 1980). Changes in air rate affect both pulp and froth sub-processes, for example low air rates giving higher bubble loading in the pulp, but with low froth mobility and long froth residence times. Emphasis has to be placed on the relative trends observed and not the absolute repeatability given the difficulty in controlling the various parameters under investigation. The relationship therefore between particle-size, air rate, PAR, liquid and solids recovery is not simple, and is likely to be system dependent.

4.4 Indicative grade and recovery curves

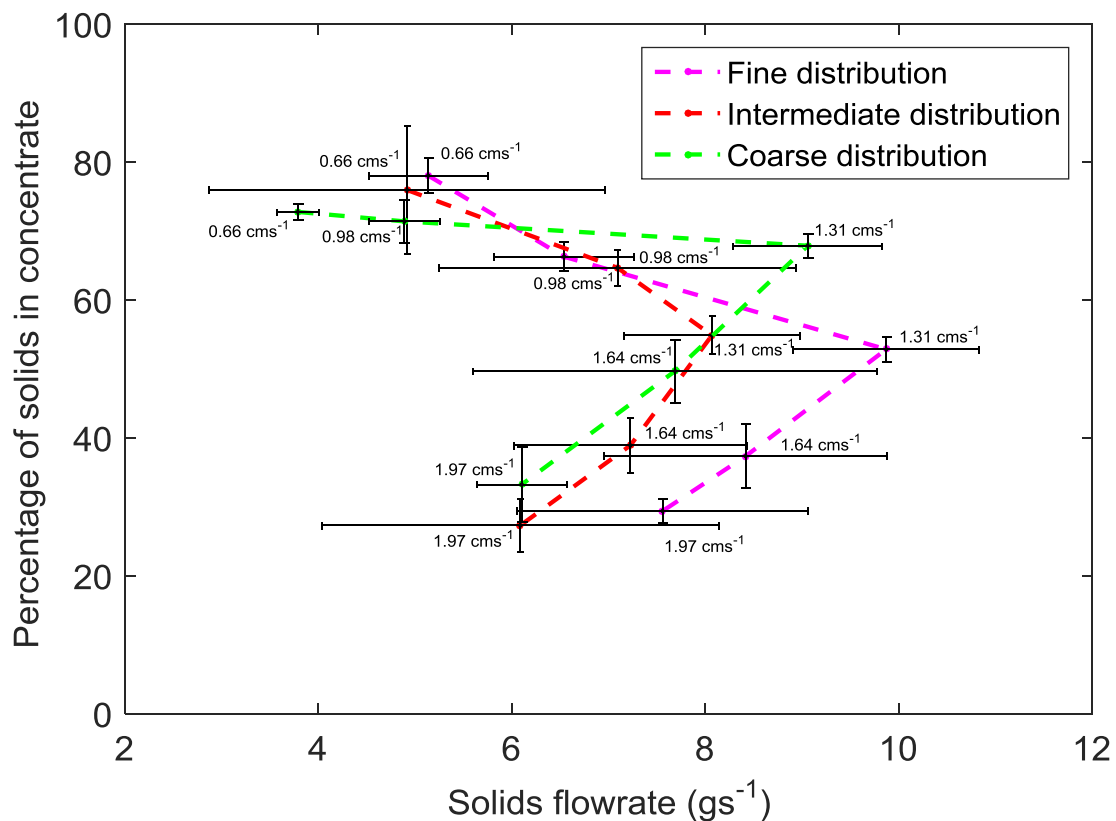


Figure 4.11 - The relationship between solids content of concentrate and concentrate solids flowrate for experiments carried out at different air rates (J_g). All errors are one standard deviation from the mean.

Errors are given as 95 % confidence intervals.

As discussed in the methodology, in a single species system it is not possible to construct a grade and recovery curve for each of the particle size distributions under investigation. However, a suitable analogy for both grade and recovery has been deduced from previous industrial data. The percentage of solids in concentrate can be taken as an indicative grade, as shown in Chapter subsection 3.5.5. As cell air rate increases, so too does the amount of liquid and gangue being entrained into the froth. This results in a drop in grade as air rate increases (Hadler et al, 2010a; Smith, Hadler and Cilliers, 2010) and also in the solids content of the concentrate, suggesting this is a useful indicator of the selectivity of the flotation system in which no separation is being undertaken. Similarly, the flowrate of solids reporting to the concentrate can be an indicator of recovery (Supomo et al., 2008), although care must be taken above PAR air rates, where mass pull increases, but recovery does not (Hadler et al, 2010a). The indicative grade recovery curves for the experiments undertaken are presented in Figure 4.11.

By presenting the data in this way, further observations can be made about the behaviour of each of the particle size distributions being tested. It can be seen that at the lower superficial gas velocities, before the peak in solids flowrate, the gradient of the decrease in solids content in the froth by mass is low. However, once the peak in solids flowrate has been passed, the ratio of liquid to solid increases far more quickly for the subsequent superficial gas velocities. This implies that once the liquid content begins to dominate in the froth, the solids content drops rapidly. For this experimental system, the higher liquid content and shorter residence times in the froth at high air rates have the potential to give more stable bubble films, in spite of the reduction in attached particles, which are no longer observed in large quantities, as suggested by the lower solids recovery.

The figure suggests that the coarse distribution results in a greater solids recovery than the intermediate distribution, and the highest overall grade. The relative grade is higher initially for the intermediate and fine distributions at a J_g of 0.66 cm s^{-1} (within error), before dropping more rapidly than the coarse distribution towards the peak flowrate at a J_g 1.31 cm s^{-1} . At the peak flowrate and below, the finest distribution has the lowest grade but the highest recovery, and the coarse distribution is has the highest grade.

Overall, it can be seen that the coarser flotation system optimizes the grade of the product whereas the finer particles optimize the recovery. However, only the coarse particle system has achieved PAR at the peak in solids flowrate and so it is difficult to draw

comparative conclusions across all particle size distributions. The breakdown of recovery mechanisms in the froth phase is also unknown from a single species system. It would be expected to see a large proportion of entrained particles at high air rates, but it is not possible to determine the recovery mechanisms in a single species system.

4.5 Chapter conclusions

It can be seen that while maintaining all other operating conditions, changes to the particle size distribution of the feed has an impact on air recovery, recovery of solid and liquid to the concentrate, and the particle size of the recovered solids in concentrate.

A reduction in particle size yields in an increase in air recovery. The peak in air recovery also shifts to higher air rates. However, air recoveries begin to exceed the 50 % threshold for the intermediate and fine particle size distributions. At high air recoveries, the link between solids and liquid content, and the air recovery breaks down (Neethling,, 2008). A peak in air recovery is therefore not necessarily expected to match the peak in solids recovered to the concentrate for these two distributions. In the coarse distribution, air recoveries remain below 50 % for all superficial gas velocities tested, and the peak in solids flowrates matches with the peak in air recovery as expected.

The solids flowrate data also indicates that there is an increase in the mass of solids recovered with a decrease in the particle size. All three systems have a peak in solids recovery at the same superficial gas velocity. For the intermediate and fine systems, the solids flowrate reduced despite an increase in air recovery at higher values of J_g . Air recovery is a function of froth stability, and therefore the liquid fraction is having a stabilizing effect on the froth phase, this is particularly evident in Figure 4.6 and Figure 4.8.

Inspection of the liquid flowrates show larger values associated with the intermediate and fine distribution in particular. At higher air rates the difference between the liquid content of the coarse and fine distributions increases, with the fine distribution associated with as much as 70-80 % more liquid.

Changes to the particle size distribution have effects on other operating parameters of the experimental system. Changing the distribution changes the total available surface area that the collector can adsorb to, changing the chemistry of the pulp phase and

ultimately affecting froth stability. Particle hydrophobicities are affected. The amount of liquid drawn into the froth phase is also affected by particle size and the hydrophobicity of the particles. It has become clear through the course of the investigation that changing just the particle size leads to a very complicated chain of effects to the behaviour of the system. This must all be considered when drawing conclusions about the system behaviour with respect to particle size.

Ultimately, when air recovery does not exceed 50 % across the range of superficial gas velocities tested, there is a peak in solids flowrate with PAR. It is also clear that adjusting the particle size distribution has consequences for other operating parameters of the experimental system, and affects froth stability. .

Chapter 5

Improving Air Recovery and flotation performance through the addition of a horizontal mesh at the pulp-froth interface

5.1 Introduction

The basic design of the majority of flotation cells has remained unchanged since their inception over 100 years ago. They have increased significantly in size and, more recently, a selection of novel designs have come to market, such as the Jameson Cell (Clayton et al., 1991) and the Eriez Hydrofloat™ (Eriez 2015). New designs improve performance through numerous mechanisms, for example through modifying the design of the mixing zone and improving the transport of bubbles to the froth phase (Clayton et al., 1991), or by increasing the frequency at which bubbles contact particles in the mixing phase (Eriez 2015). The capital expenditure of replacing entire flotation circuits is however often viewed as prohibitive, and there is a gap in the market to introduce retrofit designs to flotation cells, that would involve a significant reduction in capital expenditure over replacing the flotation units.

Turbulence has been identified as one of the most significant contributors to particle loss, e.g. Schulze (1977); Nguyen (1997) and Koh et al. (2009). In this Chapter, the effect of a retrofit design, a mesh of varying thickness and hole-size, similar to that of Zhang et al., (2009) is investigated. The mesh was chosen to reduce turbulence, and therefore loss of attached mineral at or near the pulp-froth interface. An experimental factorial design has been undertaken, investigating multiple treatments (configurations) in order to determine the significance of design variables on performance, and to improve the grade and recovery of solids to the concentrate.

5.2 Factorial Experimental Plan

The three-way factorial experimental plan was drawn up in order to determine whether mesh hole-size, mesh thickness and superficial gas velocity were resulting in significant changes to flotation performance, and to determine whether any of the treatments tested showed a statistically validated improvement over the unmodified base case. The factorial is presented below in Table 5.1. Mesh hole-size and mesh thickness, the design variables, are known as factors. The final dataset for the factorial is unbalanced, with an unequal number of repeats for the different treatments. In addition, a control experiment was undertaken and repeated 5 times throughout the course of the factorial. This allows for comparison of treatment data to determine statistically significant performance improvements.

Table 5.1 - Mesh combinations tested in the three-way factorial. M refers to mesh, the first number represents the mesh hole-size and the second mesh thickness. Each factor is tested at a J_g of 0.98 cm s^{-1} , 1.31 cm s^{-1} and 1.64 cm s^{-1} for a total of 36 treatment combinations.

MESH HOLE-SIZE (mm)	THREE FACTOR FACTORIAL DESIGN MATRIX								
	Mesh thickness (mm), at each level of J_g								
	20			30			40		
	0.98 cm s^{-1}	1.31 cm s^{-1}	1.64 cm s^{-1}	0.98 cm s^{-1}	1.31 cm s^{-1}	1.64 cm s^{-1}	0.98 cm s^{-1}	1.31 cm s^{-1}	1.64 cm s^{-1}
10	M1x2	M1x2	M1x2	M1x3	M1x3	M1x3	M1x4	M1x4	M1x4
20	M2x2	M2x2	M2x2	M2x3	M2x3	M2x3	M2x4	M2x4	M2x4
30	M3x2	M3x2	M3x2	M3x3	M3x3	M3x3	M3x4	M3x4	M3x4
40	M4x2	M4x2	M4x2	M4x3	M4x3	M4x3	M4x4	M4x4	M4x4
50	M5x2	M5x2	M5x2	M5x3	M5x3	M5x3	M5x4	M5x4	M5x4

5.2.1 Exclusion of the 10 mm hole-size

Based on initial testing of the meshes, it was noted that the 10 mm hole-size was incapable of producing a particle-stabilised froth. Although liquid and air bubbles passed through the pores, particles did not, and a poorly developed foam with negligible solids content formed. It was decided to exclude the 10 mm hole-size from the factorial based upon these observations. The mesh forms part of an investigation into the effect of mesh hole-size on liquid and solid behaviour in Chapter 6.

5.3 Unmodified base case results

The unmodified base case was tested five times over the course of the factorial plan in order to provide a control for comparison with factorial treatments undertaken. The solids distribution is the same as the coarse particle distribution in Chapter 4 and is maintained throughout the factorial. The error bars presented are for one standard deviation from the mean of all the values.

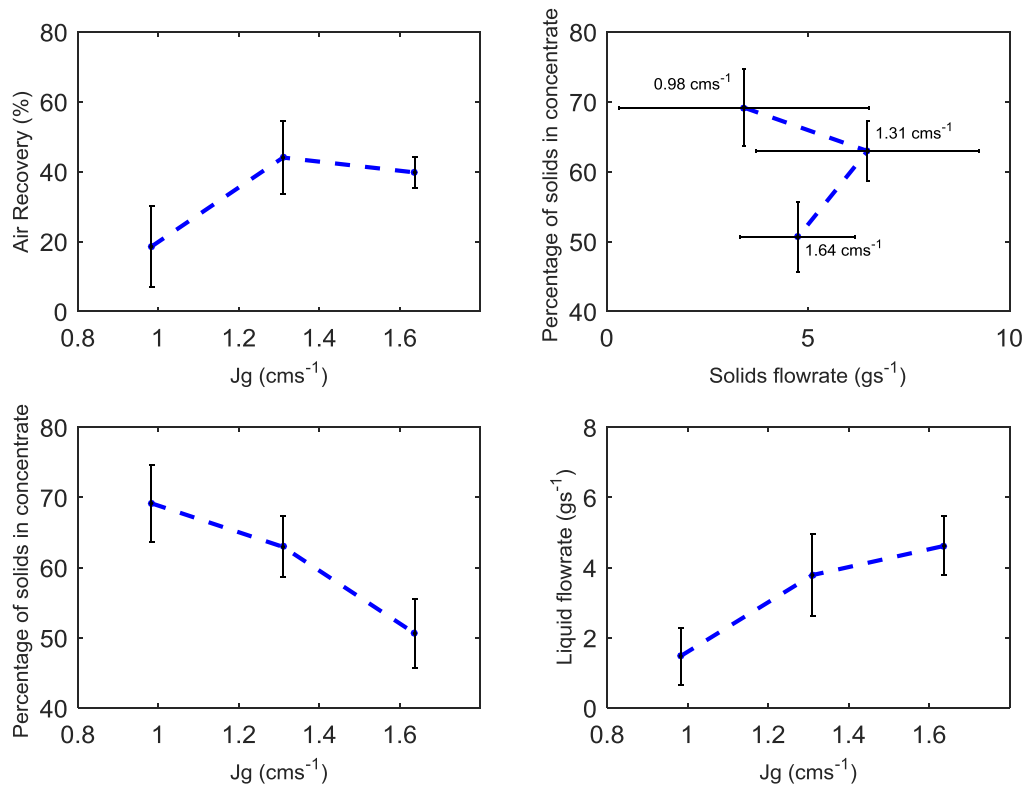


Figure 5.1 - Mean results for the unmodified experiments as carried out for comparison with the factorial experimental plan. All errors are given as 95 % confidence intervals.

Figure 5.1 plots mean results for the unmodified base case, undertaken specifically for the work in Chapter 5. Figure 5.1a indicates air recovery with superficial gas velocity, peaking at a J_g of 1.31 cms^{-1} . The peak in air recovery and peak in solids flowrate occurred at a J_g of 1.31 cms^{-1} , with the peak solids flowrate mean of 7.1 gs^{-1} as shown in Figure 5.1b. The mean performance in terms of air recovery falls broadly in line with the results presented in Chapter 4, for the same experimental system. Liquid flowrate, as shown in Figure 5.1d, increased from the lowest to the highest J_g , from 2 gs^{-1} to 4 gs^{-1} .

Solids percent in concentrate with solids flowrate (the indicative grade - recovery curve) is shown in Figure 5.1b; and indicates a peak in recovery at a Jg of 1.31 cms^{-1} . The subsequent increase in liquid flowrate at a Jg of 1.64 cms^{-1} , as shown in Figure 5.1d and a decrease in solids flowrate implies the experimental system has passed its peak recovery, and this is confirmed by the reduction in air recovery at this Jg. Grade continually increases with an increase in Jg.

These mean values provide a benchmark for all the experiments in the factorial plan. Each experiment or series of experiments is considered in reference to these values, and relevant values from this dataset is plotted on graphs throughout the following discussion.

5.4 Factorial experimental results and statistical analysis

The results of the three-way factorial are presented below, with data tables available in Appendix A. Operating performance in terms of the responses of solids flowrate, liquid flowrate, air recovery and proportion of solids in concentrate as functions of mesh hole-size, thickness and superficial gas velocity are presented. The results are presented as both the main effects (influence of only mesh hole-size, thickness and superficial gas velocity on responses) and interactions between pairs of main effects. As the factorial is unbalanced, wherever repeats are available, the results are data means of these repeats. An uneven number of repeats exist due to time constraints brought about through changes in local environment including temperature and humidity.

The three-way full factorial is then analysed using ANOVA (analysis of variance) in order to determine whether mesh hole-size and thickness at particular values of superficial gas velocity are having a statistically significant effect on flotation performance, either individually as main effects, or as interactions. Where an improvement in flotation performance is determined to exist, statistical tests are undertaken to determine their validity, comparing within treatments as well as with the unmodified base case. This analysis is undertaken at the peak in air recovery for each design, where the peak in solids flowrate is found to exist.

Note: 0 on the mesh hole-size axis refers to the unmodified base case.

5.4.1 Response of main effects (mesh hole-size, thickness and Jg)

The response plots below take the mean value across all Jg's for mesh hole-size and mesh thickness, and all mesh hole-sizes and thicknesses for Jg. CI refers errors given as a 95 % confidence interval, $\pm$ a value from the mean value given.

5.4.1.1 Air recovery

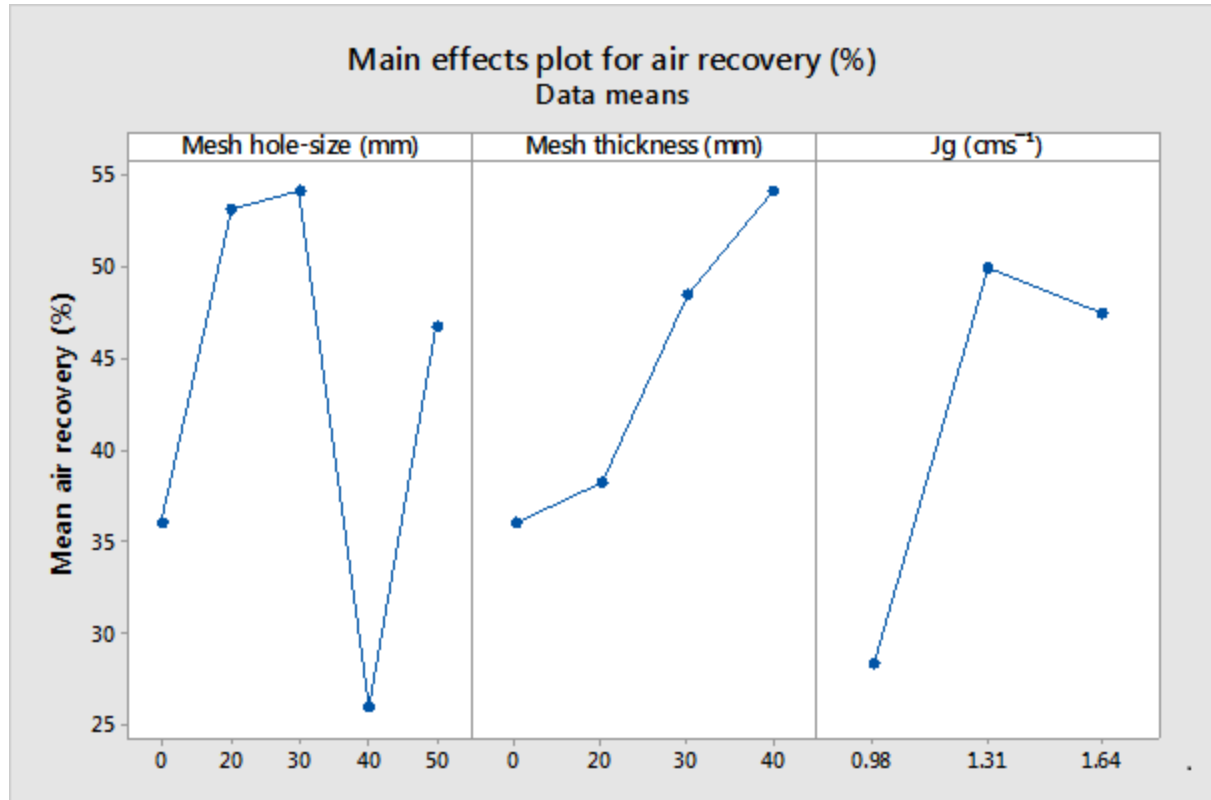


Figure 5.2 - The individual effects of mesh hole-size, thickness and Jg on air recovery for all treatment combinations on air recovery

As can be seen in Figure 5.2, air recovery is affected by all three operating parameters. Mesh hole-sizes of 20 and 30 mm have a mean air recovery of 53 and 54 %, with a CI of ± 5.41 and ± 4.16 % respectively. The values are an additional 17 % greater than the unmodified base case at 36 %. Air recovery drops approximately 30 % for the larger 40 mm hole-size mesh to 25 % ± 5.45 %, with the 50 mm hole-size seeing a recovery to 46.5 ± 5.98 %. The low mean air recovery (and performance) with the 40 mm hole-size meshes was validated through multiple repeats of the configuration. In addition, the mesh was removed during an experimental run to ensure that no other experimental variable was affecting performance. Without the mesh, the experiment produced an overflowing froth.

Considering mesh thickness, air recovery is again lowest for the unmodified base case at 36 %. With the addition of a mesh, air recovery ranges from 37-55 % with an increase in mesh thickness from 20 to 40 mm, with CI's of ± 4.02 % and ± 5.23 % respectively. Air recovery is also affected by Jg, increasing from 30 % ± 5.23 % at a Jg of 0.98 cms^{-1} to 52 % ± 3.57 % at a Jg of 1.31 cms^{-1} . Air recovery decreases to 49 % ± 5.06 % at a Jg of 1.64 cms^{-1} with a CI of. This tentatively suggests the peak in air recovery is found at a Jg of 1.31 cms^{-1} for many of the treatments.

5.4.1.2 Solids flowrate

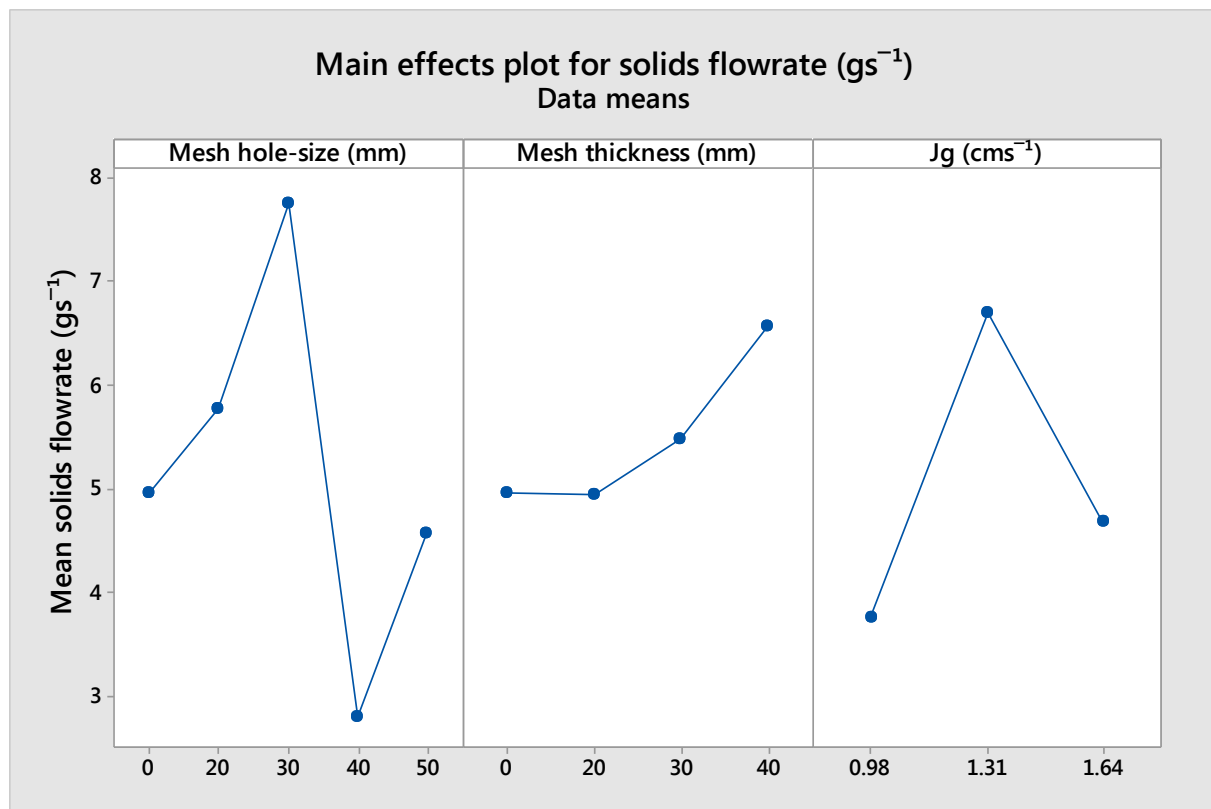


Figure 5.3 - The individual effects of mesh hole-size, thickness and Jg on air recovery for all treatment combinations on solids flowrate to the concentrate.

As can be seen in Figure 5.3, the main effects of mesh hole-size, thickness and superficial gas velocity on solids flowrate, (a proxy for recovery), have a similar shape to those observed in figure 5.6 for air recovery. Mean solids flowrate increases from 5 gs^{-1} for the unmodified system, to 5.8 gs^{-1} with a CI of $\pm 0.76 \text{ gs}^{-1}$ for the 20 mm mesh hole-size and $7.8 \pm 0.59 \text{ gs}^{-1}$ for the 30 mm hole-size. This value with the 95 % confidence limit is outside the mean of any other value, statistically validating it as the mesh hole-size with the highest solids flowrate. It then decreases to $2.9 \pm 0.77 \text{ gs}^{-1}$ for a mesh hole-size of 40

mm, (statistically significantly lower performance than all other mesh hole-sizes), with solids flowrate increasing again to $4.6 \pm 0.84 \text{ gs}^{-1}$ at a hole-size of 50 mm. A mesh thickness of 20 mm results in very similar solids flowrates to the unmodified base case. Increasing mesh thickness results in the mean solids flowrate improving from $5 \pm 0.57 \text{ gs}^{-1}$ to $6.4 \pm 0.62 \text{ gs}^{-1}$ at 40 mm. Considering the superficial gas velocity, peak solids flowrate occurs at a Jg of 1.31 cms^{-1} . This matches the observation of a peak in air recovery at a Jg of 1.31 cms^{-1} . This matches with industrial observations that the peak in solids flowrate occurs at a peak in air recovery.

5.4.1.3 Liquid flowrate

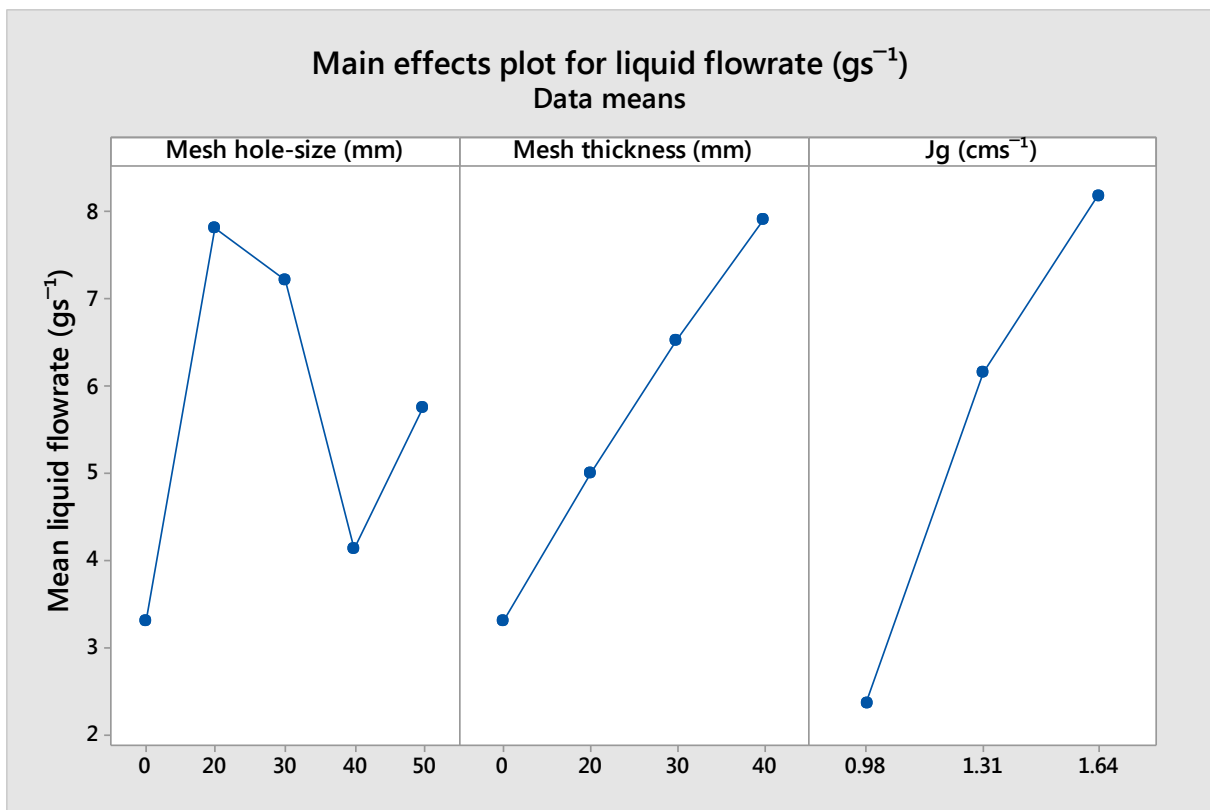


Figure 5.4 - The individual effects of mesh hole-size, thickness and Jg on air recovery for all treatment combinations on liquid flowrate to the concentrate.

As shown in Figure 5.4, mean liquid flowrate continues to increase with Jg, a trend not observed in air recovery and solids flowrate. The behaviour with respect to mesh hole-size and thickness is however similar in shape to both air recovery and solids flowrate. Liquid flowrates of 3.2 gs^{-1} are indicated for the unmodified base case. There is a considerable increase in the mean flowrate with the addition of a mesh, increasing to $7.8 \pm 0.79 \text{ gs}^{-1}$ for the 20 mm mesh hole-size, decreasing to $7.2 \pm 0.61 \text{ gs}^{-1}$ at 30 mm hole-

size, the mean values not being statistically different. There is a further decrease at 40 mm hole-size to $4 \pm 0.80 \text{ gs}^{-1}$, before increasing again at 50 mm hole-size to $5.9 \pm 0.87 \text{ gs}^{-1}$. The 40 mm hole-size results in statistically lower performance in terms of liquid flowrate. An increase in mesh thickness results in an almost linear increase in liquid flowrate from 3.2 gs^{-1} for the unmodified base case, to $5 \pm 0.59 \text{ gs}^{-1}$, $6.5 \pm 0.76 \text{ gs}^{-1}$ and $8 \pm 0.64 \text{ gs}^{-1}$ for the 20 mm, 30 mm and 40 mm mesh thicknesses respectively. Liquid flowrate also increases linearly with superficial gas velocity with a mean liquid flowrate of $2.4 \pm 0.76 \text{ gs}^{-1}$ at a J_g of 0.98 cms^{-1} to $8.1 \pm 0.74 \text{ gs}^{-1}$ at a J_g of 1.64 cms^{-1} . This links mesh thickness and superficial gas velocity increases to an increase in liquid flowrate, and these values are increasing with a greater than 95 % level of confidence in the dataset.

5.4.1.4 Solids percent in concentrate

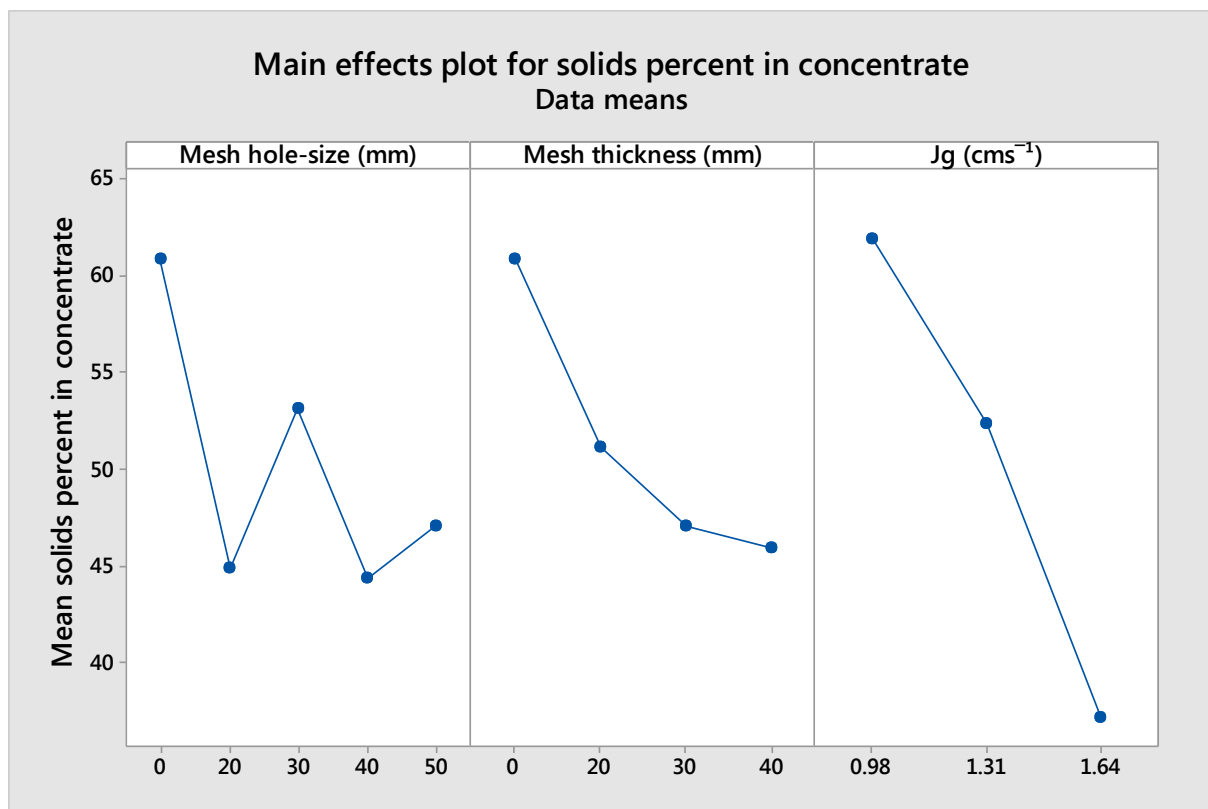


Figure 5.5 - The individual effects of mesh hole-size, thickness and J_g on air recovery for all treatment combinations on the composition of the concentrate.

The weight percentage of solids in concentrate (a proxy for grade) is shown in Figure 5.5. It can be seen that the mean proportion of solids fluctuates with mesh hole-size, and is much reduced when compared to the unmodified base case, with 61 % solids on average.

With mesh hole-size, solids content fluctuates with the highest solids content at 45 ± 3.10 % at a mesh hole-size of 20 mm to 55 ± 2.37 % with the 30 mm mesh hole-size. There is a decrease in solids content of the concentrate with an increase in mesh thickness. The unmodified base case has a mean solids content of 61 %, decreasing to a mean value of 46 ± 2.53 % at a mesh thickness of 40 mm. Superficial gas velocity has a large effect on mean solids percent in concentrate, reducing from 60 ± 3.00 to 34 ± 2.90 % solids in concentrate with an increase in J_g from 0.98 cms^{-1} to 1.64 cms^{-1} . This is linked with liquid flowrate as shown in figure 5.4, with an increase in the liquid content directly linked to a reduction in the solids content of the concentrate.

Increasing mesh hole-size results in variable, non-linear effect liquid and solids recovered to the concentrate, as well as air recovery, with the magnitude and direction of change for each hole-size consistent across all three. This implies the total volume of overflowing froth is changing in response to mesh hole-size changes. Increasing mesh thickness results in a linear response, resulting in an increase in solids and liquid flowrate, and a corresponding increase in air recovery. Increasing the superficial gas velocity results in increased liquid flowrates and reduced solids content in the froth, with air recovery and solids flowrate peaking at the same J_g of 1.31 cms^{-1} . This is typical behaviour observed in flotation on plant, with floatable mineral flowrates maximised at PAR.

5.4.2 Interactions and their statistical significance

Whether each variable, or the interaction between each variable is statistically significant can be determined by ANOVA, and is presented in this section. This can be conducted at each level of each variable, or between each individual treatment tested. The interactions of two of either mesh hole-size, mesh thickness or superficial gas velocity with respect to the third variable are considered for their effect on air recovery, solids flowrate, liquid flowrate and percentage of solids in concentrate are presented. As each point represents an individual treatment, the statistical significance of the result can be determined, relative to the unmodified system or in comparison with another result. Where repeats exist, the values in the graphs are the data means.

5.4.2.1 Air recovery

The analysis of variance for air recovery is presented below, in addition to the interactions between the variables with respect to air recovery.

Table 5.2 - ANOVA analysis of air recovery as a function of mesh hole-size, mesh thickness and Jg

Source of variation	df	Adj SS	Adj MS	F-Value	P-value
Source					
Mesh hole-size	3	8504	2834.50	25.23	< 0.001
Mesh thickness	2	1920	960.20	8.55	0.001
Jg	2	5876	2938.20	26.16	< 0.001
Mesh hole-size with thickness	6	1403	233.80	20.80	0.068
Error	63	7077	112.30		
Lack of Fit	21	2348	111.80	0.99	0.491
Pure Error	42	4729	112.60		
	76	26035			

The P-values as shown in Table 5.2 indicate there is a statistical significance associated with changes in mesh hole-size, mesh thickness and superficial gas velocity. A confidence of at least 99.999 % attached to the effect of each of these variables. The interaction of mesh hole-size and thickness is also statistically significant to a confidence of 93.2 % while the error is not statistically significant with a P-value of 0.491.

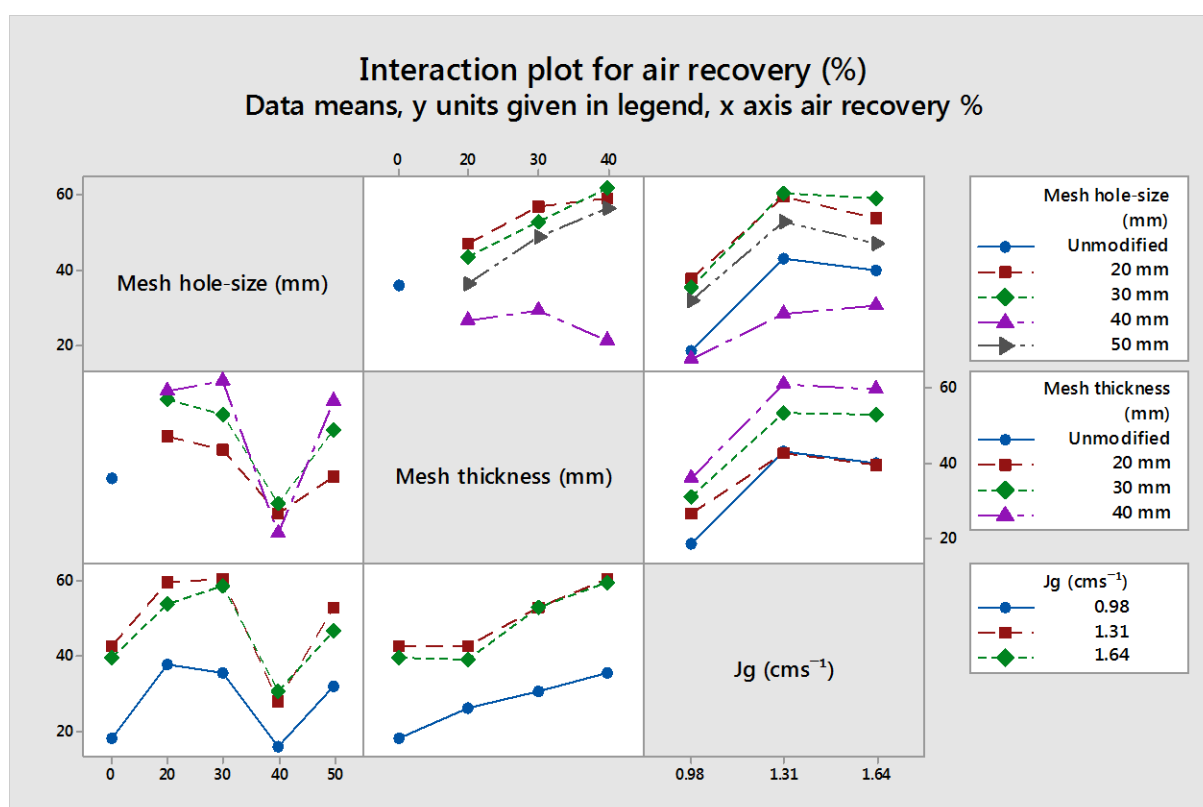


Figure 5.6 - The effect of interactions between mesh hole-size, thickness and Jg on air recovery for all treatment combinations on air recovery.

As can be seen in figure 5.6, the interactions of the operating variables results in relatively consistent trends with air recovery, effects that are statistically validated in the ANOVA. The effect of mesh hole-size is variable. Air recovery is relatively consistent between mesh hole-sizes of 20-30 mm, with values between 10-20 % greater than that of the unmodified base case. Increasing mesh thickness results in an increase in air recovery at each level of mesh hole-size. The 40 mm hole-size results in a much reduced air recovery when compared to the other mesh hole-sizes and the unmodified base case, with air recovery recovering at a hole-size of 50 mm. The low air recovery for the 40 mm configuration was validated through multiple repeats of the configuration. There are interactions between mesh hole-size and mesh thickness, indicated by the differing gradient between each mesh hole-size at each mesh thickness. This is validated in the ANOVA as being statistically significant.

Overall, air recoveries are higher than the unmodified base case with respect to both mesh hole-size and mesh thickness, except in the case of the 40 mm mesh hole-size that experiences very poor performance; and similar air recoveries with meshes with 20 mm thickness at a Jg of 1.31 cms⁻¹ and 1.64 cms⁻¹. The highest air recovery is noted at mesh hole-size of 30 mm and thickness of 40 mm (M3x4 mesh). Air recovery typically peaks at a Jg of 1.31 cms⁻¹ for each treatment tested.

5.4.2.2 Solids flowrate

The Analysis of variance for solids flowrate is presented below, in addition to the interactions between the variables with respect to solids flowrate.

Table 5.3 - ANOVA analysis of solids flowrate as a function of mesh hole-size, mesh thickness and the superficial gas velocity.

Source of variation	df	Adj SS	Adj MS	F-Value	P-value
Source					
Mesh hole-size	3	244.580	81.527	41.380	< 0.001
Mesh thickness	2	6.176	3.088	1.570	0.217
Jg	2	144.133	72.066	36.580	< 0.001
Mesh hole-size with thickness	6	44.183	7.364	3.740	0.003
Error	63	124.110	1.970		
Lack of Fit	21	40.439	1.926	1.926	0.519
Pure Error	42	43.671	1.992		
	76	608.804			

The P-values as shown in Table 5.3 indicate there is a statistical significance associated with changes in mesh hole-size and superficial gas velocity. A confidence of at least 99.999 % attached to the effect of both of these variables. The effect of mesh thickness cannot be treated as significant with low confidence at 78.3 % (an equivalent risk of 21.7 % that there is no significance). This can be observed in figure 5.11. However, the interaction of mesh hole-size and thickness is also statistically significant to a confidence of 99.7 % while the error is not statistically significant with a P-value of 0.519.

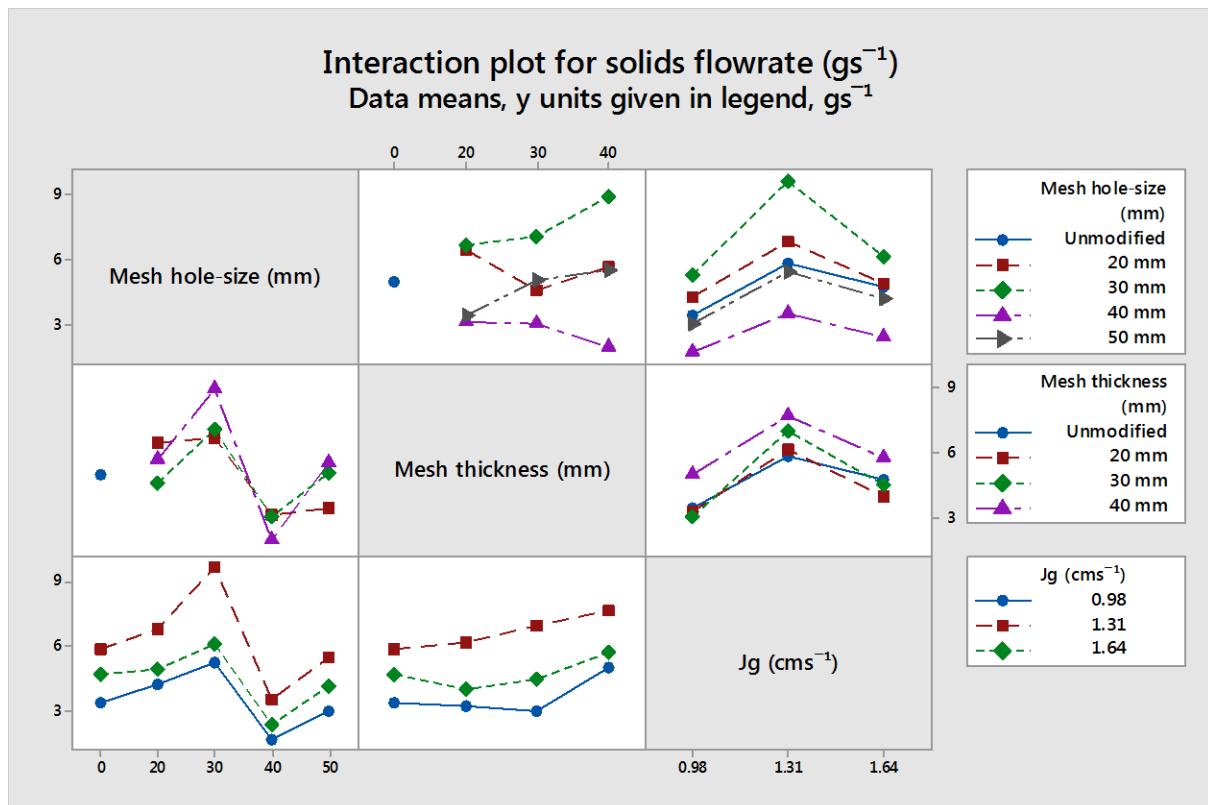


Figure 5.7 - The effect of interactions between mesh hole-size, thickness and Jg on solids flowrate for all treatment combinations.

Trends relating to solids flowrate are more difficult to discern in the factorial as shown in Figure 5.7. Solids flowrate at 20 mm mesh hole-size is approximately similar to the unmodified base case. It then increases with an increase in mesh hole-size from 20 to 30 mm where it peaks. There is then a decrease in solids flowrate at a hole-size of 40 mm before increasing at a hole-size of 50 mm. The ANOVA indicates a statistical significance to the variability observed. However, there is no clear pattern with respect to mesh thickness, the optimal thickness varying from hole-size to hole-size, and this is reflected in its high P-value of 0.217 (lack of confidence), as indicated by the ANOVA in Table 5.3.

The interaction of mesh thickness and hole-size results in variable solids flowrate with an increase in mesh hole-size, and these interactions are statistically significant as indicated in table 5.3. Peak solids flowrate is found to exist with the M3x4 treatment combination. With respect to Jg, the trends are clear, with the greatest solids flowrates occurring at a superficial gas velocity of 1.31 cms^{-1} , for a mesh hole-size of 30 mm and a mesh thickness of 40 mm (M3x4). Generally, the trends observed in solids flowrate are very similar to the trends observed in air recovery.

5.4.2.3 Liquid flowrate

The analysis of variance for liquid flowrate is presented below, in addition to the interactions between the variables with respect to liquid flowrate.

Table 5.4 - ANOVA analysis of liquid flowrate as a function of mesh hole-size, mesh thickness and the superficial gas velocity.

Source of variation	df	Adj SS	Adj MS	F-Value	P-value
Source					
Mesh hole-size	3	130.790	43.596	17.260	< 0.001
Mesh thickness	2	94.570	47.284	18.720	< 0.001
Jg	2	428.850	214.424	84.900	< 0.001
Mesh hole-size with thickness	6	21.340	3.556	1.410	0.226
Error	63	159.110	2.526		
Lack of Fit	21	41.240	1.964	0.700	0.809
Pure Error	42	117.870	2.806		
	76	852.970			

The P-values as shown in Table 5.4 indicate there is a statistical significance associated with changes in mesh hole-size, mesh thickness and superficial gas velocity on liquid flowrate. A confidence of at least 99.999 % attached to the effect of each of these variables. The interaction of mesh hole-size and thickness is not significant, with low confidence at 77.4 % while the error is not statistically significant, with a P value of 0.809.

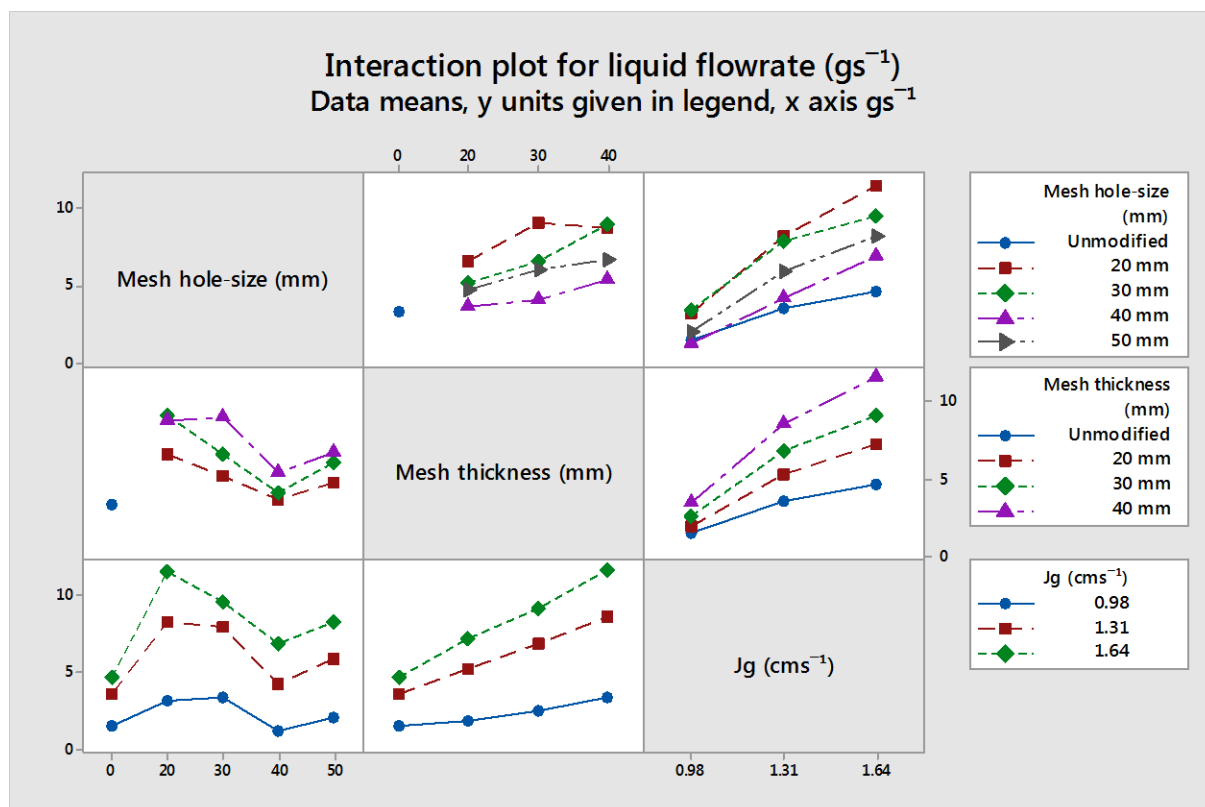


Figure 5.8 - The effect of interactions between mesh hole-size, thickness and Jg on liquid flowrate for all treatment combinations.

Figure 5.8 describes how liquid flowrate varies with mesh hole-size, thickness and superficial gas velocity. With respect to mesh hole-size and thickness, the unmodified base case has the lowest liquid flowrates. Liquid flowrate continually increases with an increase in mesh thickness from 20 to 40 mm, with liquid flowrates more than doubling between the unmodified base case and the 40 mm mesh thickness at higher values of Jg. The ANOVA indicates there is a statistical significance attached to the increase in liquid flowrates. The addition of meshes with a hole-size of 20 or 30 mm results in increased liquid flowrates compared to the unmodified system. The addition of a 40 mm mesh hole-size reduces liquid flowrates, but not as low as the unmodified base case, with a 50 mm hole-size resulting in liquid flowrates between the 40 mm mesh hole-size and the 30 mm mesh hole-size. There is a statistical significance associated with the effect of hole-size on liquid flowrates. Changes in Liquid flowrates increase with an increase in superficial gas velocity, with smaller hole-sizes and increased mesh thickness associated with the highest liquid flowrates, and the unmodified system with the lowest.

5.4.2.4 Solids percent in concentrate

The analysis of variance for the percentage of solids in concentrate is presented below, in addition to the interactions between the variables with respect to the percentage of solids in concentrate.

Table 5.5 - ANOVA analysis of the percentage of solids in concentrate as a function of mesh hole-size, mesh thickness and the superficial gas velocity.

Source of variation	df	Adj SS	Adj MS	F-Value	P-value
Source					
Mesh hole-size	3	1671	557	17.720	< 0.001
Mesh thickness	2	936.900	468.430	14.900	< 0.001
Jg	2	6652.500	3326.260	105.800	< 0.001
Mesh hole-size with thickness	6	788.400	788.400	4.180	0.001
Error	63	1980.700	31.440		
Lack of Fit	21	621.700	29.600	0.910	0.575
Pure Error	42	1359	32.360		
	76	11455.800			

The P-values as shown in table 5.5 indicate there is a statistical significance associated with changes in mesh hole-size, mesh thickness and superficial gas velocity on solids percent in concentrate. A confidence of at least 99.999 % attached to the effect of each of these variables. The interaction of mesh hole-size and thickness is also statistically significant to 99.999 %. The error is not statistically significant with a P-value of 0.575.

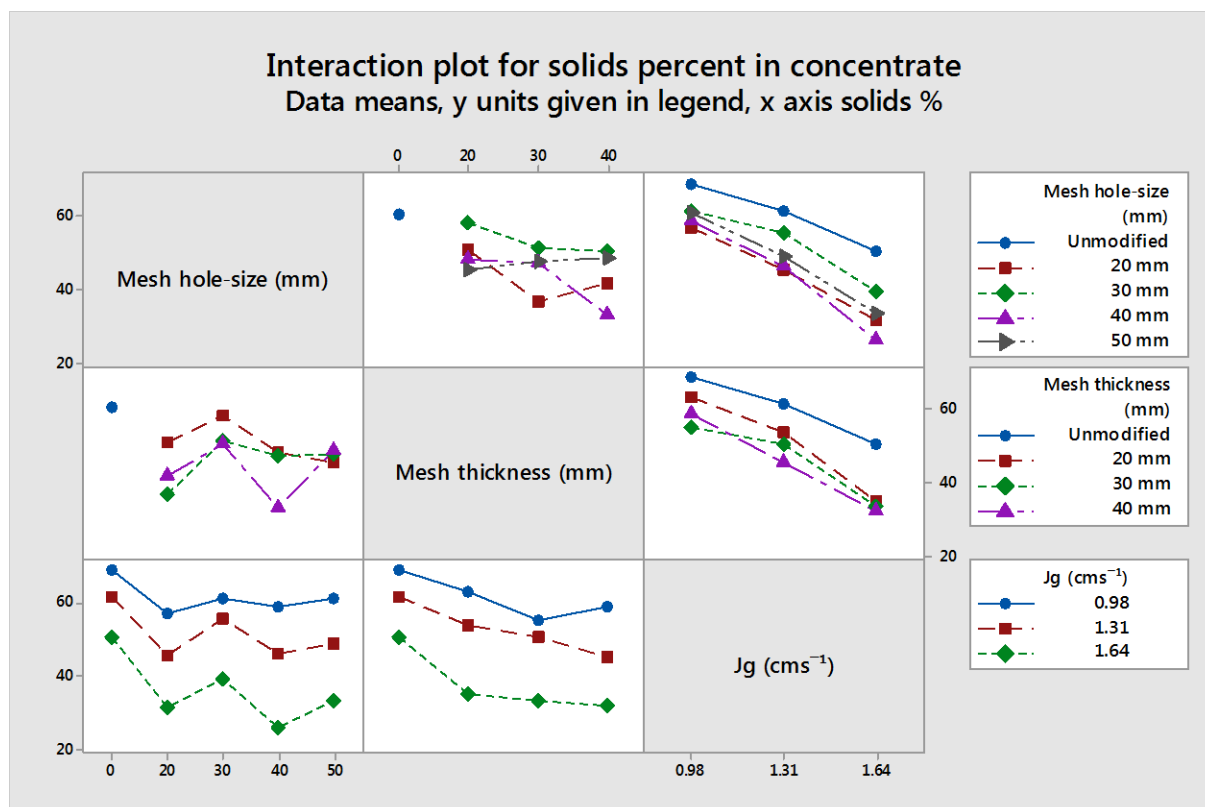


Figure 5.9 - The effect of interactions between mesh hole-size, thickness and J_g on solids percent in concentrate for all treatment combinations.

Figure 5.9 describes how the percentage of solids in concentrate, the indicative grade is affected by mesh hole-size, thickness and the superficial gas velocity. As shown in Table 5.5, there is statistical significance associated with the effect of all three variables on the percentage of solids in concentrate, as well as the interaction of mesh hole-size and thickness. The highest percentage of solids in concentrate are associated with the unmodified base case, and the lowest superficial gas velocities. In almost all cases, increasing the thickness of the mesh results in a decrease in the solids content of the froth, as does increasing the superficial gas velocity. This is linked to increases in the liquid flowrate and content of the froth. The solids percent in concentrate with respect to mesh hole-size is variable; the highest percentage of solids in concentrate is associated with the 30 mm mesh hole-size. In all cases, relative to the unmodified base case, grade in the froth is reduced.

5.4.3 Discussion

Considering air recovery, solid and liquid recovery and the percentage of solids in concentrate, it is clear that mesh hole-size, mesh thickness and superficial gas velocity have a statistically significant effect on the behaviour of the system.

Mean air recovery increases in the majority of cases, and the peak in air recovery at a J_g of 1.31 cm s^{-1} is linked to the peak in solids flowrate in all but one case. The addition of meshes in several configurations in many cases improves solids flowrates relative to the unmodified base case, indicative of increased recovery.

All responses are affected in a similar manner by mesh hole-size, the effect of which is variable as mesh hole-size increases. A 10 mm hole-size results in no froth being produced, whereas there is a significant improvement at 20 mm and peak solids flowrate occurs at 30 mm hole-size. At 40 mm there is a large reduction in performance and showing some recovery at 50 mm. This implies that the mesh hole-size is having an effect on the total amount of froth produced and overflowing. This is a benefit of the mesh design.

An increase in mesh thickness appears to have a linear effect on both solid and liquid flowrates, increasing in all cases as shown in Figure 5.7. This can be linked to observed reductions in the percentage of solids in concentrate, implying some reduction in grade when compared to the unmodified base case. The improved solids flowrate is linked to improved recovery in true flotation systems, as indicated in. The mean percentage of solids in concentrate is lower in all configurations, compared to the base case. As this is an analogue for grade, it cannot be concluded that grade is improved by the use of meshes in the flotation cell.

The analysis of variance indicates whether there are statistically significant differences between mean values within variables such as mesh hole-size or thickness, and it shows that performance is being affected with statistical significance. It cannot confirm whether turbulence is reduced at the pulp-froth interface, and this requires further investigation. In addition, the factorial cannot compare between individual treatments, or a treatment with a control in order to determine the best performing configuration with statistical significance. Further statistical testing is required in order to determine the best design configuration.

5.4.4 The statistical significance of improvements in performance

Statistical tests can be undertaken between designs in order to determine if they are significantly different; and whether one mesh configuration improves over the unmodified base case with

Some of the mesh designs indicate a potential increase in solids flowrate. An increase in solids flowrate is desirable as it is indicative of improved recovery in true flotation systems. As the peak in air recovery occurs at a superficial gas velocity of 1.31 cm s^{-1} , and this is linked to a peak in solids flowrate in all but one case, statistical significance will be determined at this value of J_g .

Solids percent in concentrate, the indicative grade, is not shown to increase in any of the design configurations tested. A statistical test will be carried out at PAR air rate in order to confirm this observation.

5.4.4.1 Comparisons between designs: recovery

As can be seen in Figure 5.7, when considering mesh hole-size and thickness with respect to indicative recovery, the largest solids flowrate is associated with the M3x4 mesh design, a 30 mm hole-size and 40 mm mesh thickness.

In order to determine if this design has the highest solids flowrate with statistical significance to the 95 % confidence level, Dunnett's test, a statistical test to determine whether a treatment is statistically significant has been undertaken.

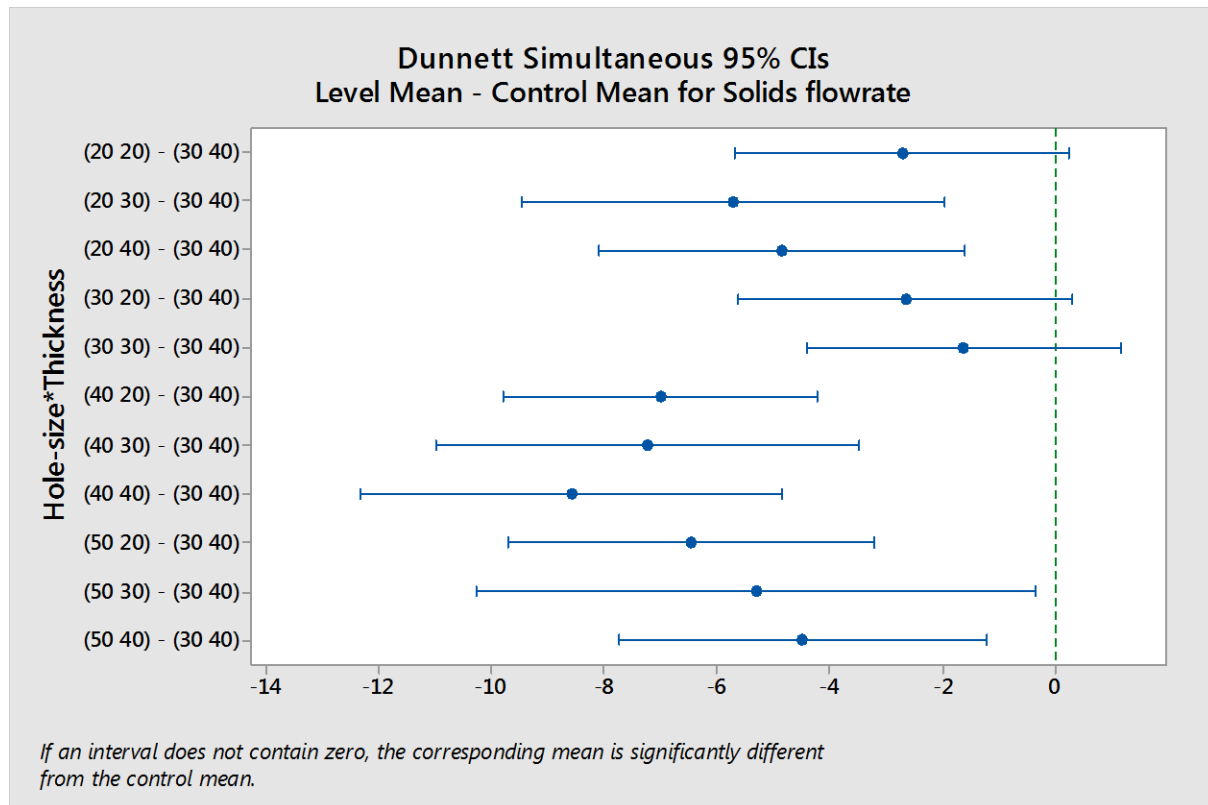


Figure 5.10 - Dunnnett's test to determine the relative statistical significance of solids flowrate for the M3x4 mesh (30 40) compared to all other mesh configurations. CI refers to confidence interval; the dashed line represents the mean value of M3x4 solids flowrate

As can be seen in figure 5.10, in all but three cases, the M3x4 mesh has been shown to have an increased solids flowrate with statistical significance to the 95 % confidence level. The means of the three remaining designs are to the left of the mean line for the M3x4 mesh at 0 on the x axis, implying their means are of a lower flowrate relative to the M3x4, and the M3x4 mean is towards the edge of the upper confidence limit for these designs. It is therefore likely that the M3x4 is the best performing design in terms of solids flowrate at a Jg of 1.31 cms^{-1} .

5.4.4.2 Comparison with the unmodified base case: recovery

In order to compare the M3x4 mesh with the unmodified base case, a one-way two sample t-test for comparing means with equal variances has been undertaken. This determines whether the M3x4 shows improvement relative to the unmodified base case in terms of solids flowrate. The results of the t-test are presented below in table 5.6.

Table 5.6 - One-way two sample t-test for comparing means with equal variances for the solids flowrate of the unmodified base case compared with the M3x4 mesh.

	Unmodified base case	M3x4
Mean	6.46700	10.91800
Variance	5.90927	2.867576
Standard deviation	2.43089	1.693392
Observations	10	6
Pooled Variance	4.82295	
Hypothesized Mean Difference	0	
df	14	
t Stat	-3.92479	
P(T<=t) one-tail	0.00076	
t Critical one-tail	1.76131	
P(T<=t) two-tail	0.00153	
t Critical two-tail	2.14479	

As can be seen in Table 5.6, the small P-value for the one sided t-test, as highlighted in yellow, indicates there is very low risk that the two means are not statistically significant. The means are different to a confidence of 99.9993 %, suggesting the M3x4 mesh improves solids flowrate, indicative recovery, compared to the unmodified base case at the peak in air recovery.

5.4.4.3 Comparisons between designs: grade

As can be seen in Figure 5.9, mean percentage of solids in concentrate for the unmodified base case is always larger than any treatment tested in the factorial. However, this needs a statistical confirmation. M3x2 (30 mm hole-size 20 mm thickness) appears to have the highest percentage of solids in concentrate of any of the configurations tested, and Dunnett's test between designs has been run in order to determine the significance of this observation.

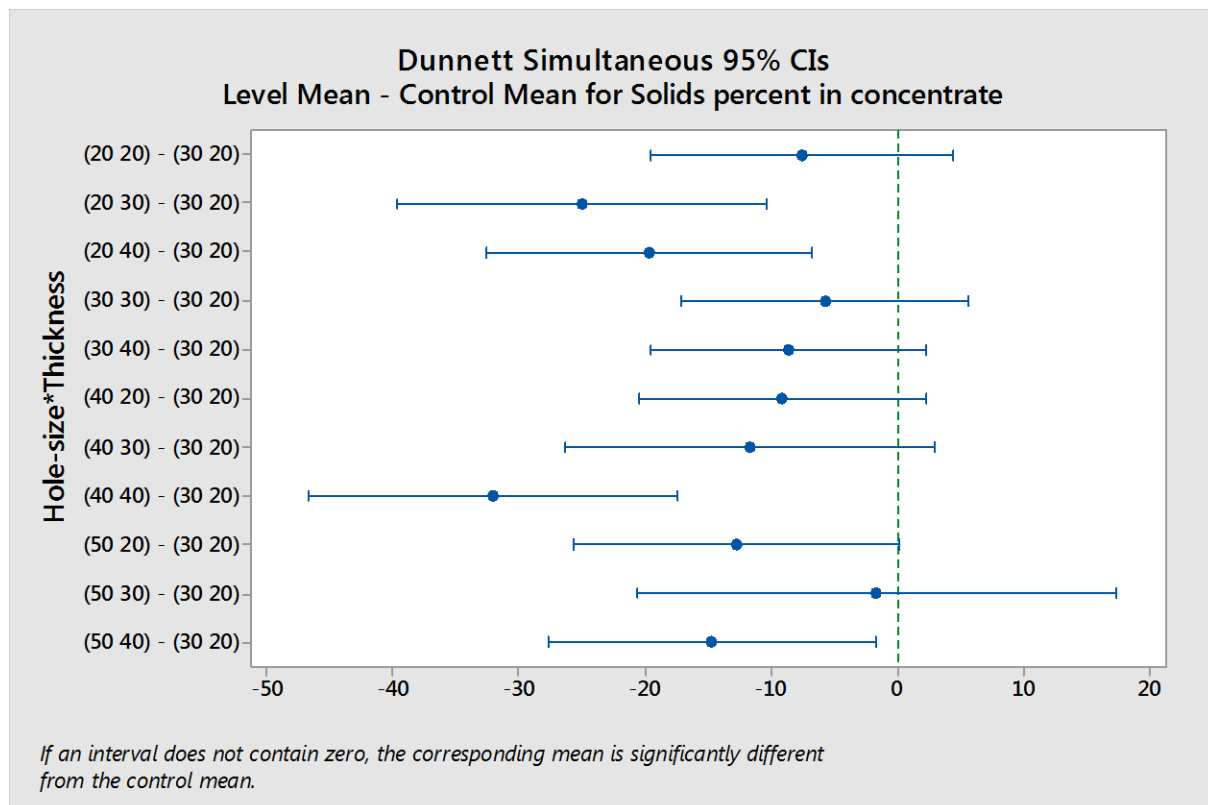


Figure 5.11 - Dunnett's test to determine the relative statistical significance of the percentage of solids in concentrate (indicative grade) for the M3x2 mesh (30 20) compared to all other mesh configurations CI refers to confidence interval, the dashed line represents the mean percentage of solids in concentrate for the M3x2 mesh

As can be seen in Figure 5.11, all mean percentage of solids in concentrate for all configurations are to the left of the mean for the M3x2 mesh. However, many are not statistically different from the M3x2 mesh at the 95 % level. Regardless, as the mean value is the largest solids percentage in concentrate, it is selected for comparison with the unmodified base case. If the comparison yields a low statistical significance, it can be assumed that no mesh design improves indicative grade.

5.4.4.4 Comparison with the unmodified base: grade

As with recovery, a one-way two sample t-test for comparing means with equal variances has been undertaken. This determines whether the M3x2 shows improvement relative to the unmodified base case in terms of percentage of solids in concentrate. The results of the t-test are presented below in Table 5.7.

Table 5.7 - One-way two sample t-test for comparing means with equal variances for the solids percent in concentrate for the unmodified base case compared with the M3x2 mesh.

	Unmodified base case	M3x2
Mean	61.75539	61.02670
Variance	27.73677	40.81419
Standard deviation	5.26657	6.38859
Observations	10	4
Pooled Variance	31.00613	
Hypothesized Mean Difference	0	
df	12	
t Stat	0.22120	
P(T<=t) one-tail	0.41433	
t Critical one-tail	1.78229	
P(T<=t) two-tail	0.82866	
t Critical two-tail	2.17881	

The table indicates that the mean indicative grade of the M3x2 mesh is not significantly better than the unmodified base case. The P-value is high at 0.414. As the M3x2 mesh has the greatest mean solids percent in concentrate, 0.73 % lower than the mean unmodified base case, it can be stated that there is no improvement in indicative grade with meshes.

5.5 Chapter conclusions

The experimental factorial examined the effect of mesh hole-size, thickness and superficial gas velocity on flotation performance. The results revealed a statistically significant improvement in at least one configuration, that of the M3x4 mesh in solids flowrate, indicative recovery, when compared to the unmodified base case.

Solids flowrate is variable with mesh hole-size, and increases with an increase in mesh thickness. The mesh designs are all also associated with an increase in liquid flowrate and air recovery. The percentage of solids in concentrate (indicative grade) drops with the inclusion of a mesh, with the M3x2 design, with the highest mean percentage of solids in concentrate showing no statistical difference from the unmodified base case.

In all cases except the 40 mm mesh hole-size, there is an increase in air recovery. Increased air recovery may be linked to increased liquid flowrates, with liquid helping to stabilise the froth phase. The peak in air recovery also continues to match with the peak in solids flowrate. Increased liquid flowrates may also be a mechanism for improved solids

flowrates, with increased solids entrained into the froth. The thicker meshes result in higher liquid and solids flowrates.

The ANOVA of the factorial suggests the interaction of mesh thickness with mesh hole-size plays an important role in improving solids flowrate for the M3x4 configuration. However, performance varies widely with mesh hole-size, whereas it improves with an increase in mesh thickness, and there is statistical significance associated with these changes. It is important to understand why high solids flowrates occur at a mesh hole-size of 30 mm and a mesh thickness of 40 mm, not only relative to the unmodified system, but in comparison with other configurations. In addition, the mesh was chosen to reduce turbulence at the pulp-froth interface. However, the factorial gives no indication as to whether the meshes have a turbulence reducing effect on particles.

In order to understand these effects, a PEPT investigation has been undertaken, as discussed in the next Chapter, in order to determine the effect of mesh hole-size and mesh thickness on flotation performance and turbulence near the interface. The M3x4 mesh is compared with the unmodified base case, as well as the M1x4, M5x4, and M3x2 mesh configurations. The investigation considers how the extremes of mesh hole-size and thickness affect particle behaviour in the pulp and froth phase compared to the unmodified base and the optimal case.

In conclusion, mesh hole-size and thickness have a statistically significant effect on flotation performance. At least one configuration, the M3x4 mesh, has a statistically significant improvement in solids flowrate compared to the unmodified base case, indicative of recovery in true flotation systems. Although no improvement in grade is detected by the factorial, there is still potential for the mesh to be used in flotation circuit design. The mesh may for example be beneficial in rougher cells on plant, where an initially higher recovery of desired mineral to the concentrate outweighs grade, which is maximised in cleaner cells further down the circuit.

Chapter 6

Position Emission Particle Tracking in flotation cells and overflowing froths

6.1 Introduction

It was determined in Chapter 5 that the addition of a retrofit horizontal mesh, with a range of hole-sizes and thicknesses had a statistically significant effect on flotation performance. In addition, one treatment, a mesh of 30 mm hole-size and 40 mm thickness, was shown to result in a significantly larger solids flowrate when compared to the control, an unmodified base case. It is not known from the factorial design whether turbulence is reduced at the pulp-froth interface.

It is necessary to understand the effect of the meshes, which result in response and performance changes. Position Emission Particle Tracking, or PEPT, provides an opportunity to make both qualitative and quantitative assessments of the behaviour of particles within the pulp and froth. The position of radioactive particles with hydrophobic or hydrophilic coatings is determined with the use of a Position Emission Tomography (PET) camera. The tracers act as analogues for mineral and gangue, and much can be determined about the behaviour of hydrophobic and hydrophilic particles in flotation systems from the collected data.

6.2 Unmodified base case

For the experiments conducted in this Chapter, a standard unmodified base case was developed as a control for comparison. An example of the unmodified base case PEPT data for a hydrophobic tracer is presented in both the vertical and horizontal slice as shown in Figure 6.1 and Figure 6.2 respectively indicating bulk flow. Indications of speed, standard deviation of speed and tracer occupancy in the cell for both hydrophobic and hydrophilic tracers are subsequently discussed.

The experiment was undertaken with the PEPT particle size distribution discussed in Chapter 3, with a superficial gas velocity of 1.38 cm s^{-1} . Data is collected for 100 minutes, and is averaged from the entire domain onto 2D slices through the flotation cell.

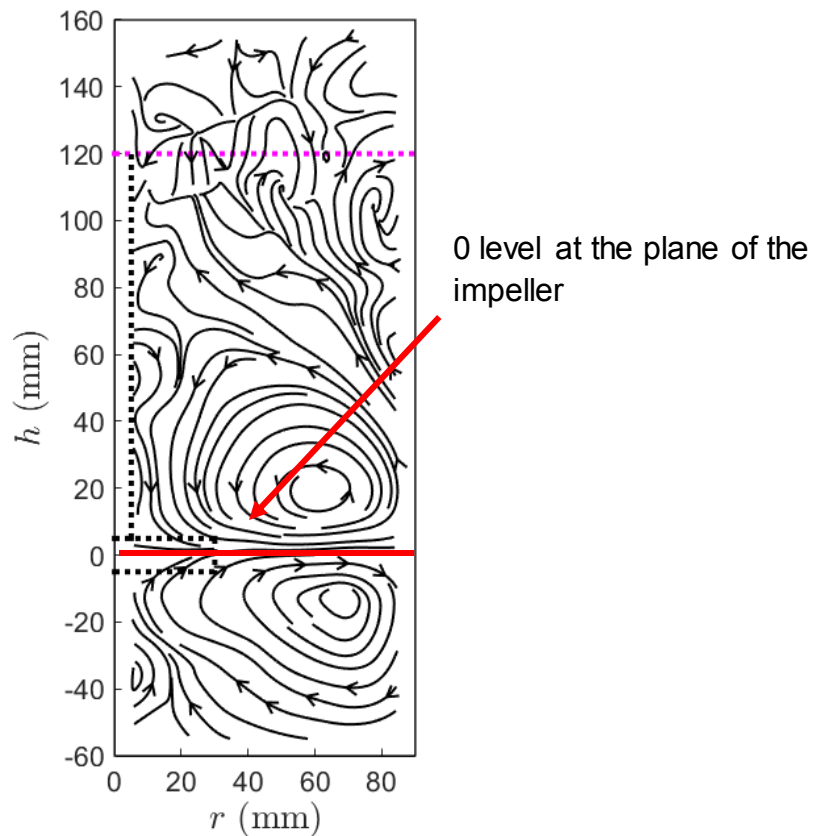


Figure 6.1 - Vertical slice through the flotation cell. The vertical slice is taken at the mid baffle angle, 45° , for the hydrophobic tracer. The plane displays the net vertical bulk flow in the flotation cell. The dashed pink line is the lip of the flotation cell, the black dashed line is the outline of the impeller and shaft.

6.2.1.1 Bulk flow in the horizontal and vertical planes

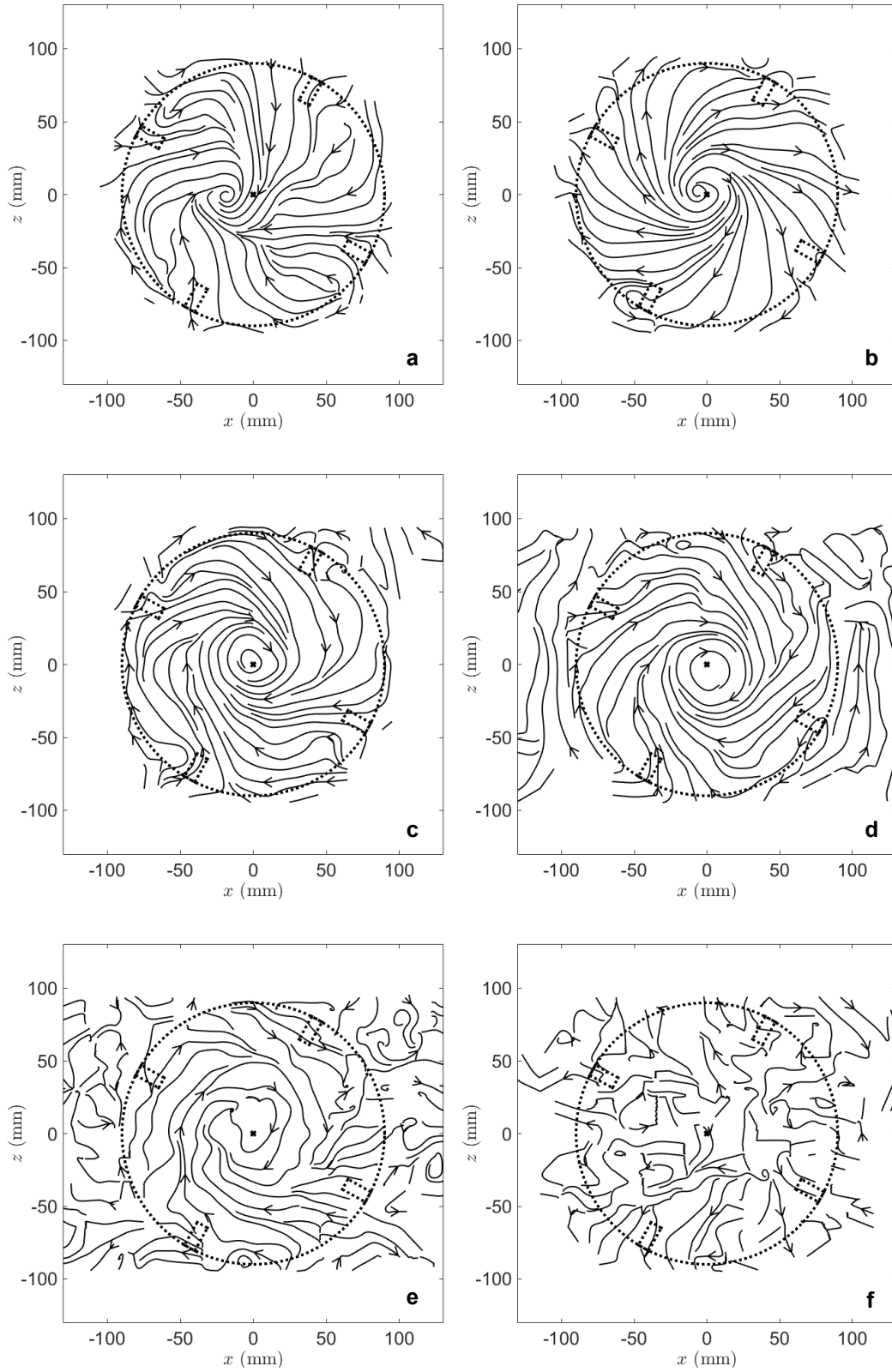


Figure 6.2 - Horizontal planes through the unmodified base case at the -30 (a), 0 (b), 30 (c), 60 (d), 90 (e) and 120 (f) mm cell planes as indicated in the previous figure. 0 (b) is the plane of the impeller. Bulk flow switches from a circular pattern in the base of the cell to square pattern above the plane of the impeller.

As can be seen from Figure 6.2 and Figure 6.1, a distinct flow pattern develops in the horizontal and vertical slices. In the vertical plane, as shown in Figure 6.1, two mixing loops develop from the plane of the impeller. The first is anticlockwise and moving up the cell wall, and the second clockwise and moving down the cell wall from the plane of the impeller. As shown in Figure 6.2a through Figure 6.2d, considering the bulk flow in the horizontal plane as shown at the -30, 0, 30 and 60 mm cell slices with respect to the impeller, there is a circular rotation developing below and in the plane of the impeller, and a square flow developing in the upper mixing loop. The swirl persists up to the pulp-froth interface, resulting in turbulent conditions, which are detrimental to the recovery of attached particles. This circulation; or swirl in the froth has for the first time been revealed.

Above the upper mixing loop in the vertical slice as shown in Figure 6.1, flow moves from the cell wall towards the impeller shaft. At the 80 mm level is the interface between the pulp and froth phase. Further mixing develops in the region above the 80 mm mark by the cell wall. In the froth, as shown in the horizontal slice in Figure 6.2e, it is shown that the swirl persists into the lower froth, indicating the lower froth is a turbulent environment. The 120 mm plane (Figure 6.2f), at the lip level of the cell, shows that the swirl has broken down, and there is a net movement of the flow of the tracer towards the lip of the cell, where it overflows into the concentrate.

For the first time, it has been demonstrated that swirl exists at the pulp-froth interface and into the lower froth phase. This is a turbulent environment and is likely to be detrimental to the recovery of attached particles across the interface and into the froth. Subsequent tests all show variations on this pattern with respect to changes in the cell superficial gas velocity and the addition of meshes.

6.2.1.2 System stability

The PEPT experiments require a steady state system over several hours. Air recovery is a measure of froth stability, and consistent behaviour with time is shown in Figure 6.3, Figure 6.4 and Figure 6.5. This experimental system was run at a J_g of 1.38 cm s^{-1} with the experimental conditions outlined in Chapter 3 for the PEPT experimental system. Air recovery and its components, froth velocity and the overflowing froth depth, are shown to behave consistently with time, indicating steady state behaviour. The large error in overflowing froth depth is related to windows in the froth where the laser can penetrate deeper and give shallower froth depth measurements.

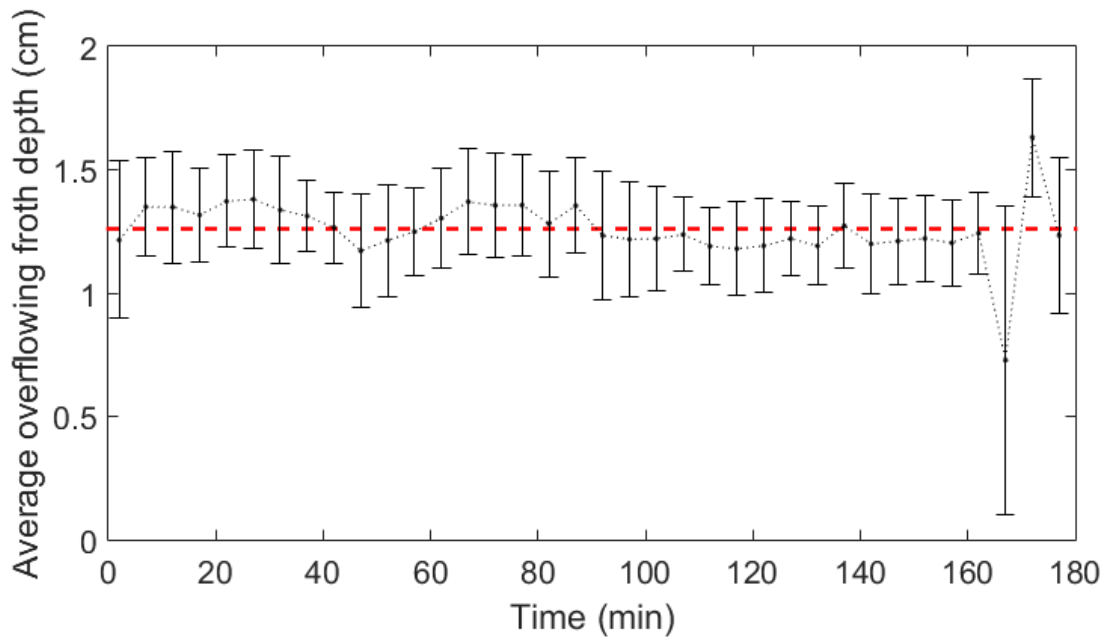


Figure 6.3 - Average overflowing froth depth with time for the experimental system. Error given as one standard deviation from the mean.

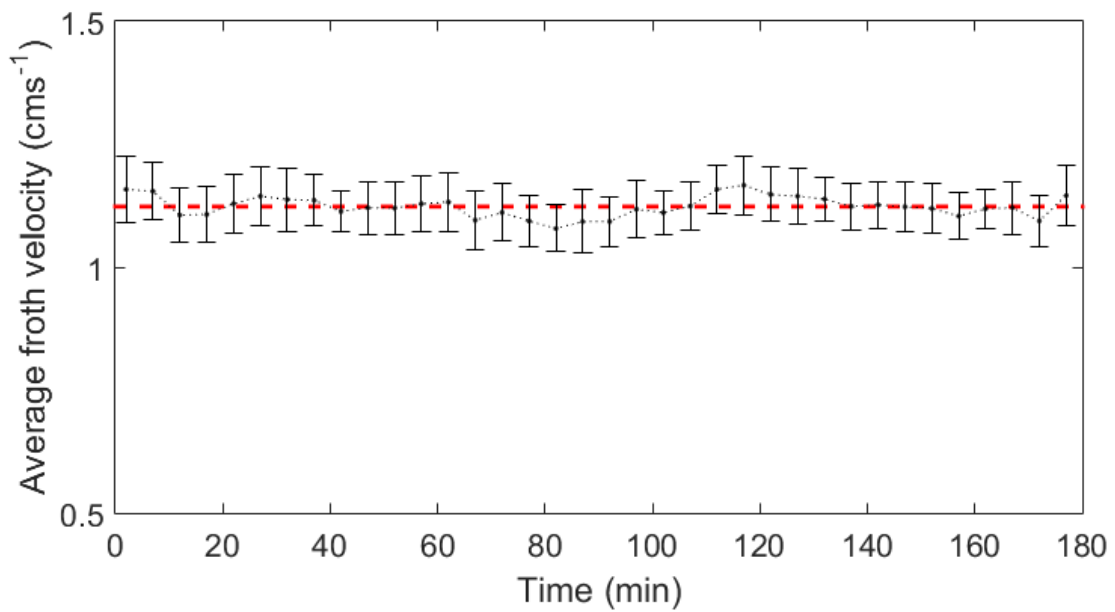


Figure 6.4 - Average overflowing froth velocity with time for the experimental system. Error given as one standard deviation from the mean.

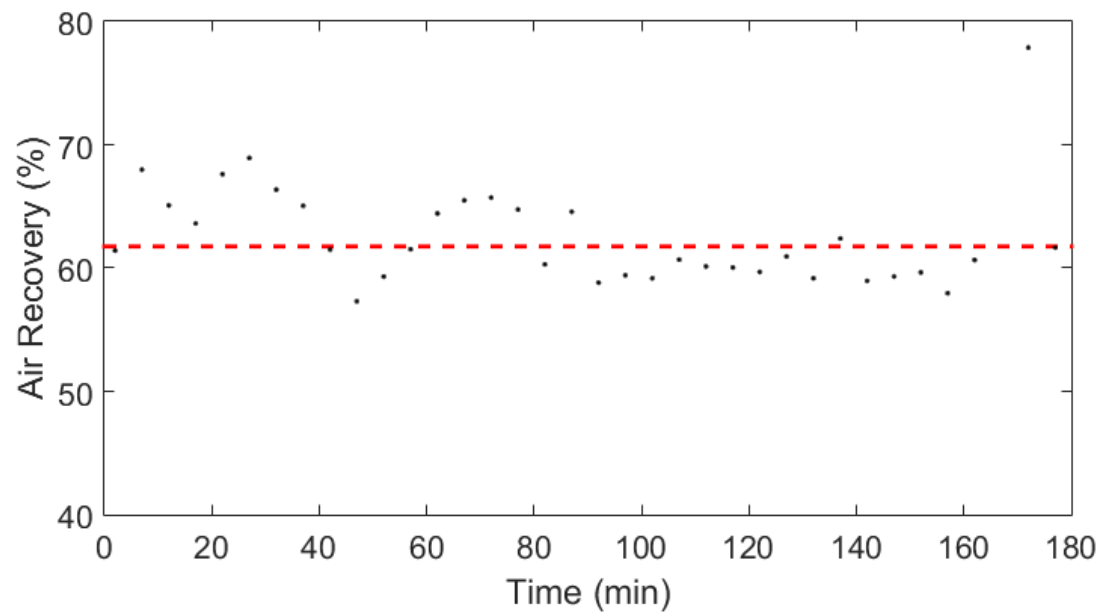


Figure 6.5 - Average air recovery with time for the experimental system.

6.3 PEPT and mesh modifications

As stated in Chapter 5, the effect of mesh hole-size and thickness is statistically significant, with one treatment, M3x4, resulting in an increased solids flowrate, indicative of recovery. It is critical to understand the cause of these changes in flotation behaviour.

6.3.1 PEPT investigation

Due to limited time and resources, a selection of meshes were chosen for investigation, rather than the whole factorial design outlined in Chapter 5.

Table 6.1 - Mesh factorial experimental plan, with meshes tested with PEPT highlighted in yellow.

MESH HOLE-SIZE (mm)	FACTORIAL DESIGN MATRIX		
	Mesh thickness (mm)		
	20	30	40
10	M1x2	M1x3	M1x4
20	M2x2	M2x3	M2x4
30	M3x2	M3x3	M3x4
40	M4x2	M4x3	M4x4
50	M5x2	M5x3	M5x4

Table 6.1 highlights the meshes investigated. These meshes were chosen as the M3x4 mesh represents the best performing mesh in terms of solids flowrate, and other meshes represent the extremes of mesh hole-size and thickness with respect to this configuration. The meshes were tested at a single air rate 21 Lpm^{-1} , which corresponds to a J_g of 1.38 cms^{-1} . The results of the mesh modifications as a function of bulk flow, tracer velocity, standard deviation of velocity and occupancy of the tracers in the experimental system are presented below. Concentrate measurements are not obtained due to the difficulty in accessing the system in the camera, and the dangers associated with leaching of tracers into the sample.

6.4 Tracer behaviour in the vertical slice

The effect of adding each of the meshes are shown in vertical slices with respect to the unmodified base case in this section. The tracer bulk flow patterns as well as tracer interactions as a function of mesh hole-size and mesh thickness are discussed.

* Varying mesh hole-size

Circulation of liquid between the holes of the mesh. The tracer is entrained through the cells into the froth

Eddies form between holes in the mesh, some downwards flow is generated but the tracer has a tendency to move back up again into the froth phase

An eddy formed within a cell in the mesh, the flow is downwards from the froth. This has a negative effect on solids moving into the froth phase

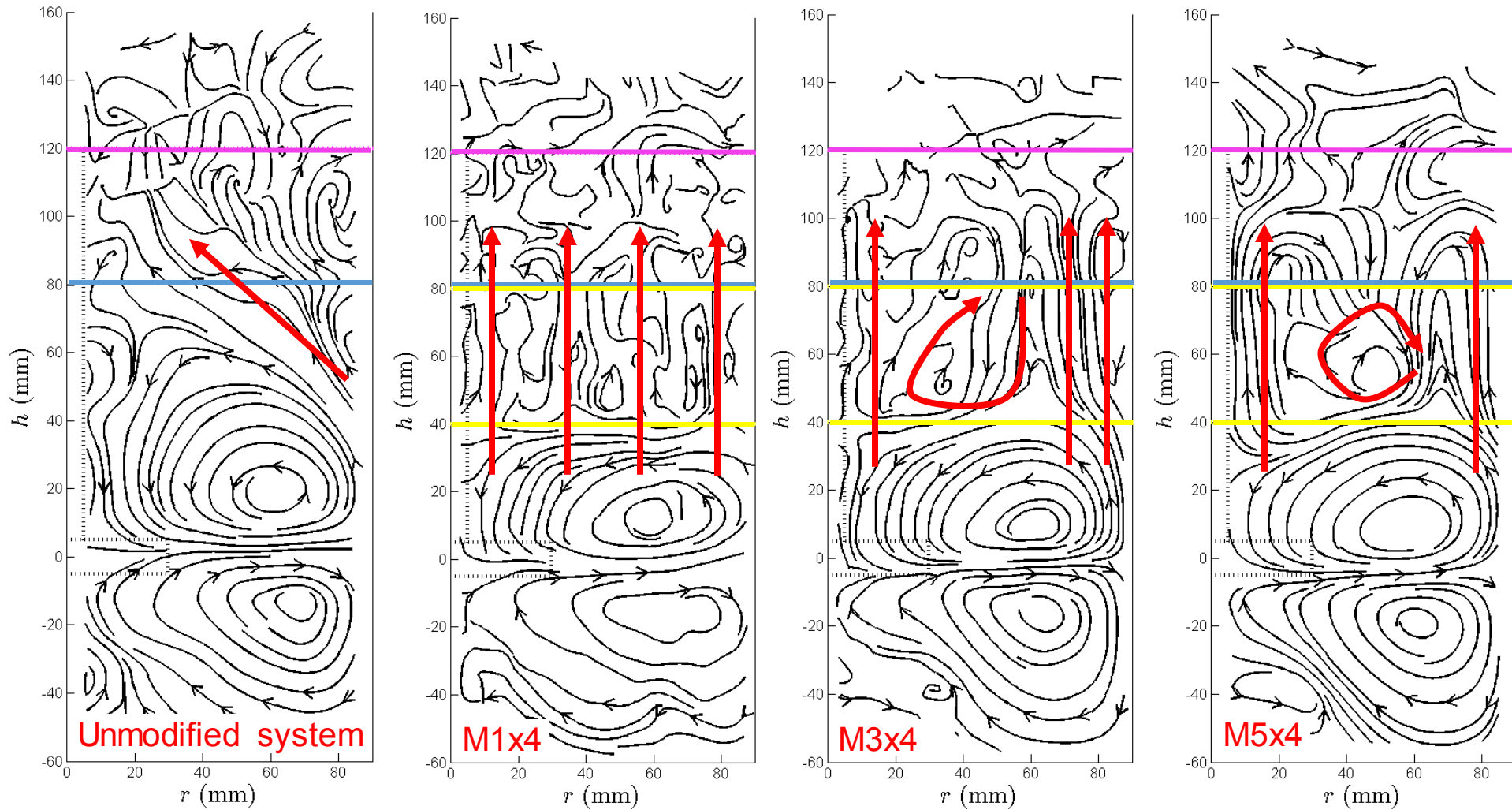


Figure 6.6 - Streamlines indicating the hydrophobic tracer bulk flow within the flotation cell, from left to right, unmodified base case, M1x4, M3x4 and M5x4. Yellow lines denote the position of the mesh, the blue line the pulp-froth interface and the pink line the lip of the flotation cell. Red arrows highlight flow patterns

*** Varying mesh thickness**

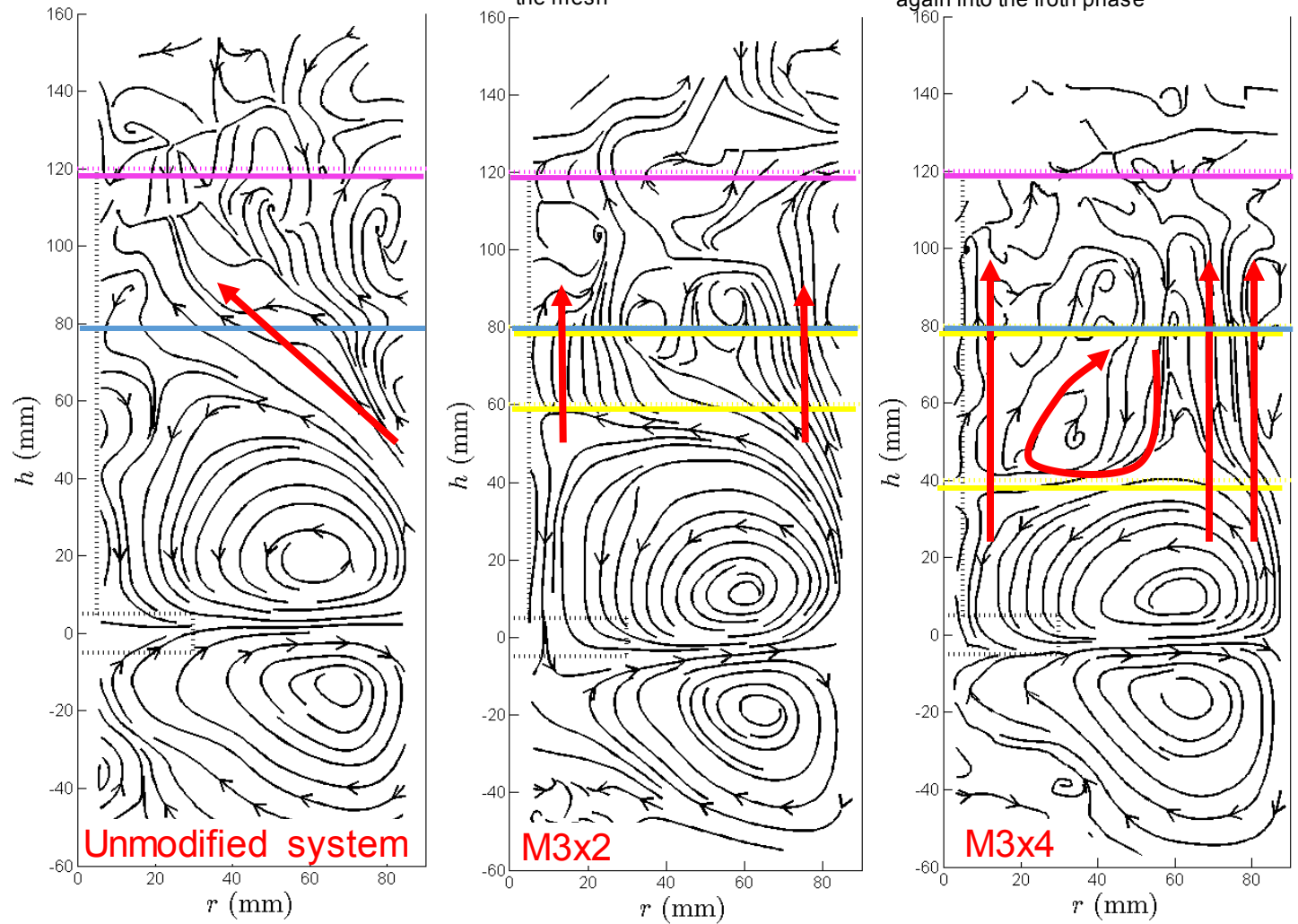


Figure 6.7 - Streamlines indicating the hydrophobic tracer bulk flow within the flotation cell, from left to right, unmodified base case, M3x2 and M3x4. Yellow lines denote the position of the mesh, the blue line the pulp-froth interface and the pink line the lip of the flotation cell. Red arrows highlight flow patterns

6.4.1 Bulk flow tracer behaviour

Figure 6.6 and Figure 6.7 display the bulk flow patterns for the hydrophobic tracers for all meshes tested, averaged in the vertical plane. In both figures, the plot to the left is the unmodified base case. The impeller mixes both the bottom and middle third of the flotation cell (This is consistent across all designs, however, thicker meshes compress the upper mixing loop). The streamlines move from the edge of the cell towards the impeller shaft in the top third, the tracer ascending from the upper mixing loop. The tracer transfers into the froth (above 80 mm height), and outwards to overflow the cell. Below the lip of the cell, a downwards loop is noted, that may have a detrimental effect on performance, pulling the tracer away from the froth. Much of the net flow of the tracer is away from the edge of the flotation cell. This is not the desired behaviour as we wish to direct the hydrophobic tracer towards the edge of the flotation cell.

All meshes result in alterations to the bulk flow of the hydrophobic tracer. These changes may be beneficial or detrimental to the performance of the flotation system. As the experimental system does not produce a particle-stabilised froth, changes in bulk flow behaviour are related to the performance of the various designs as indicated in Chapter 5.

Figure 6.6 considers the meshes of 40 mm thickness and hole-sizes of 10, 30 and 50 mm. For the M1x4 mesh, the streamlines indicate laminar axial flow upwards through the mesh. The tracer is most likely being entrained, as particle-stabilised bubbles cannot penetrate the mesh, as indicated in Chapter 5.

In this system, a liquid stabilised froth is produced above the mesh. The movement of the tracer, as represented by the streamlines, is poorly resolved. There is no accurately resolvable horizontal plane through the mesh, as the flow field is vertical through the holes and horizontal motion is at a resolution smaller than can be detected.

The larger 30 mm hole-size of the M3x4 mesh alters the bulk flow of the hydrophobic tracer. Many streamlines pass axially through the mesh, in the majority of cases towards the wall of the flotation cell, but also towards its centre. In the middle of the mesh, a circulation draws the tracer from the edge of the cell. An eddy forms within the mesh and the tracer circulates within before re-emerging upwards into the froth. Almost all the net flow through the mesh results in the transfer of the tracer from the pulp to the froth phase; the tracer moves upwards and overflows. The froth in the central region of the M3x4 cell

as shown in Figure 6.6 appears to be stagnant and has little operational benefit. As noted in Chapter 5, the M3x4 results in a statistically significant increase in solids flowrate. This is likely to be associated with the increased number of streamlines emplacing the tracer into the froth from the pulp through the mesh, bearing in mind the M1x4 mesh does not produce a particle-stabilised froth.

The M5x4 mesh, in contrast, displayed relatively poorer performance in the factorial in Chapter 5, with high liquid flowrates and reduced solid flowrates relative to the M3x4 mesh. Inspection of the plot in Figure 6.6 provides insight as to this behaviour occurs. There is a positive movement of the tracer up the wall of the flotation cell and in the centre of the cell; however a large eddy forms at the centre of the mesh. This circulation appears to capture the tracer, either preventing it entering, or removing it from the froth above. This effect is likely to be disrupting the stability of the froth above the mesh. If the tracer exits the eddy it can then move upwards and overflows the cell. The overflowing froth in this case has streamlines emanating from the centre of the cell. The large mesh hole-size appears to allow for the generation of these loops in the centre of the mesh to the detriment of flotation performance, as suggested by solids flowrates in Chapter 5.

Figure 6.7 considers thickness variation in the mesh, comparing two meshes with 30 mm hole-size, one with 20 mm thickness and the other with 40 mm, M3x2 and M3x4 respectively. The M3x2 mesh was positioned in line with the top of the thicker meshes. The thinner mesh allows for an expanded region of mixing in the pulp, similar to the unmodified base case but with flow directly upwards into the froth. As with the thicker mesh designs, solid and liquid passes through the mesh towards the wall and in the centre of the cell. In the middle of the mesh, small eddies form at the top of the mesh holes and appear to dissipate into the froth. There is net upwards and outwards flow of the tracer across the radius of the froth.

Gradual decrease in mean speed of the tracer from the pulp towards the froth. Low speeds in the froth phase with variable speeds in the froth.

Compression of the mixing region below the mesh. Very low speeds through the mesh and in the pulp above. High speeds towards the centre of the cell in the froth

Compression of the mixing region below the mesh. Relatively high speeds towards the cell wall through the mesh, with a lower velocity towards the centre. Higher speeds in the froth near the lip

Compression of the mixing region below the mesh. Relatively high speeds towards the cell wall and centre of cell through the mesh. Low velocity mixing region in the centre of the cell and low froth speeds

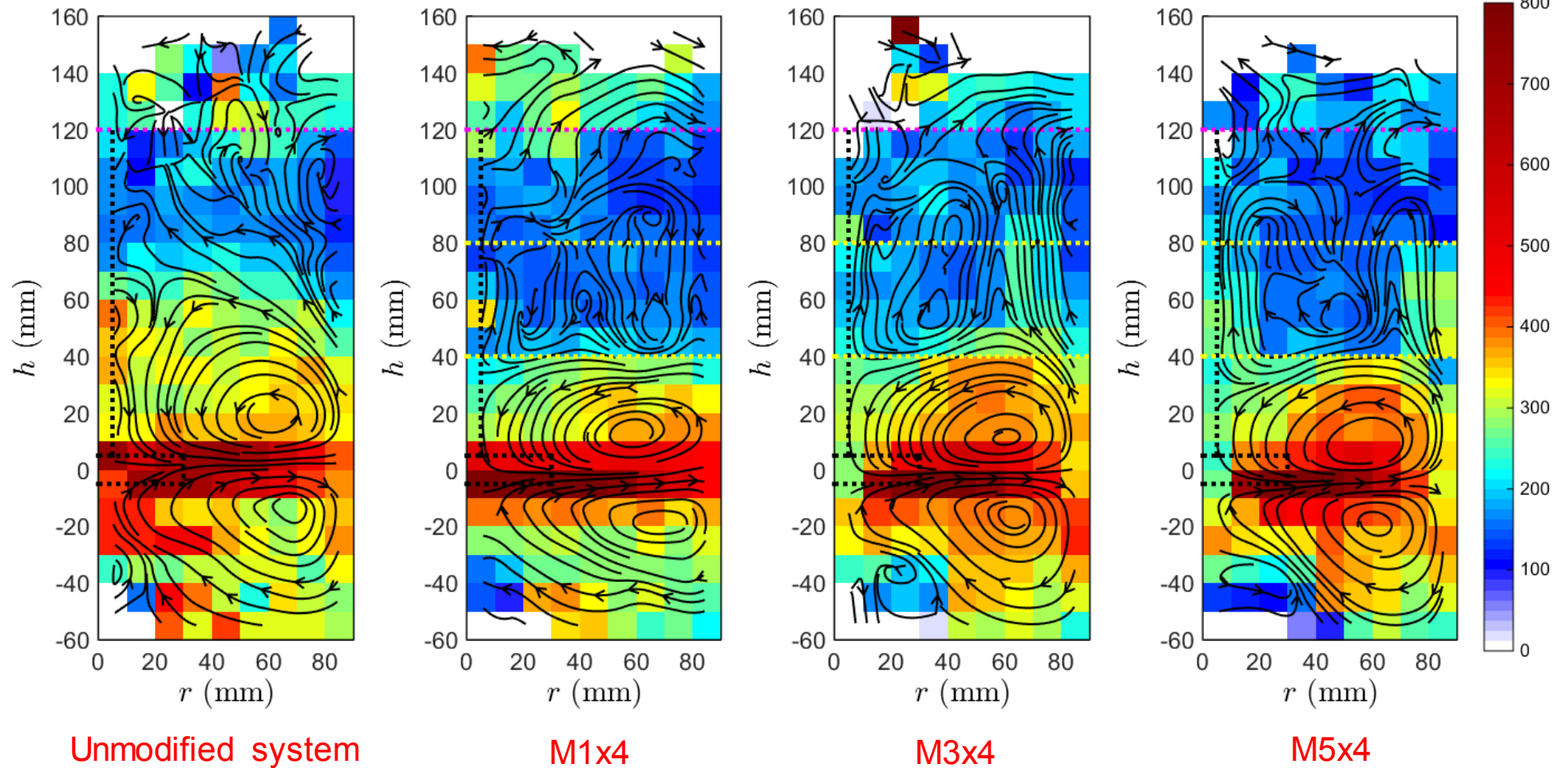


Figure 6.8 - Mean speed (mms^{-1}) per 10 mm^2 for the hydrophobic system, with the base case compared to the M1x4, M3x4 and M5x4 meshes in the vertical plane of the flotation cell (effect of mesh hole-size on mean speed). Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

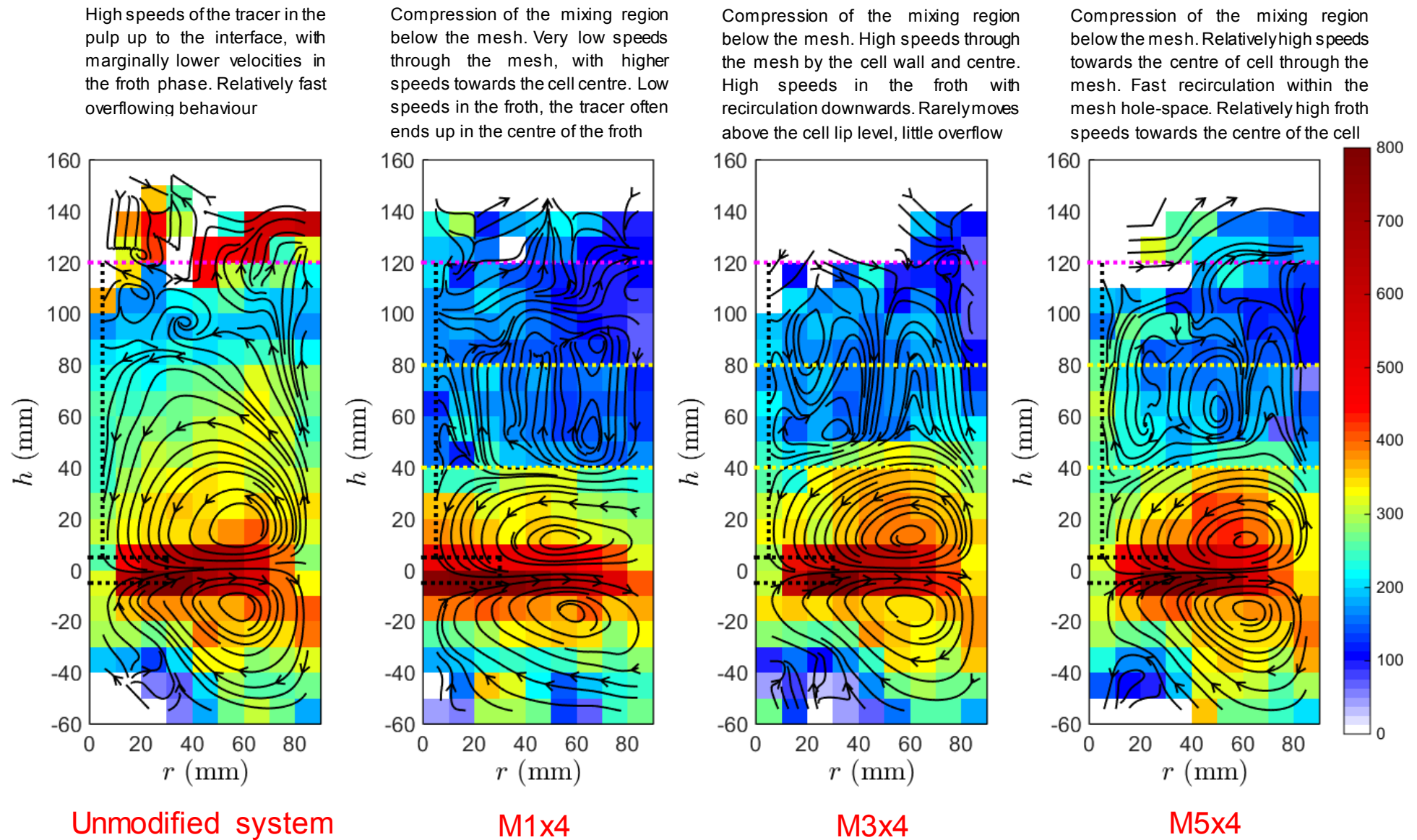
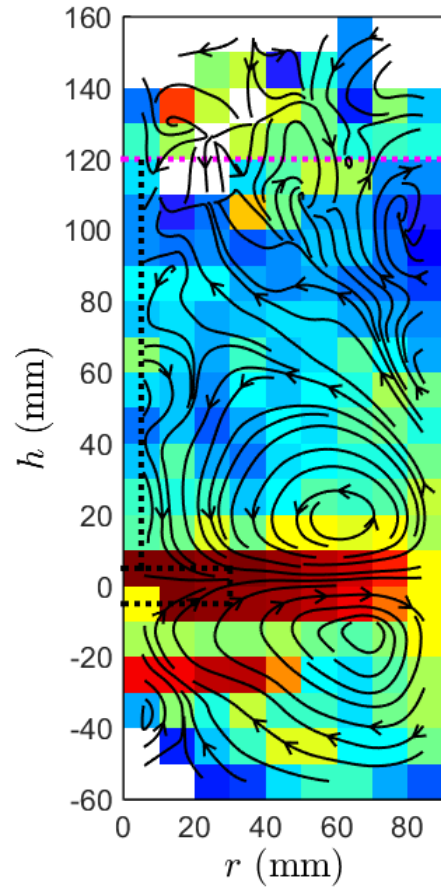


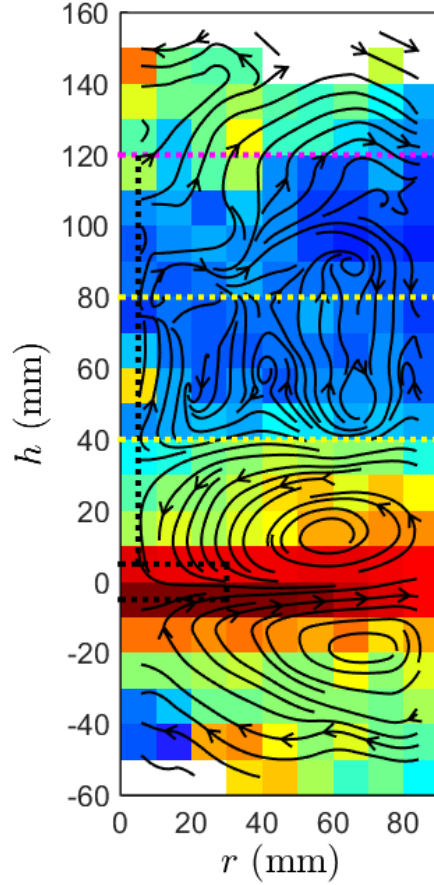
Figure 6.9 - Mean speed (mms^{-1}) per 10 mm^2 for the hydrophilic system, with the base case compared to the M1x4, M3x4 and M5x4 meshes in the vertical plane of the flotation cell (effect of mesh hole-size on mean speed). Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

High turbulence in the mixing zone, gradual decrease into the froth and high turbulence in the froth phase



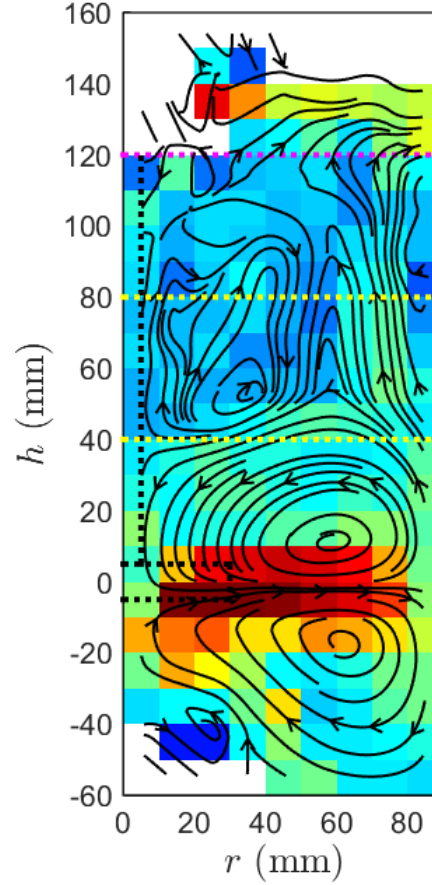
Unmodified system

Compression of the mixing region below the mesh. Very low turbulence through the mesh and in the pulp above. Higher levels of turbulence towards the centre of the cell and in the froth



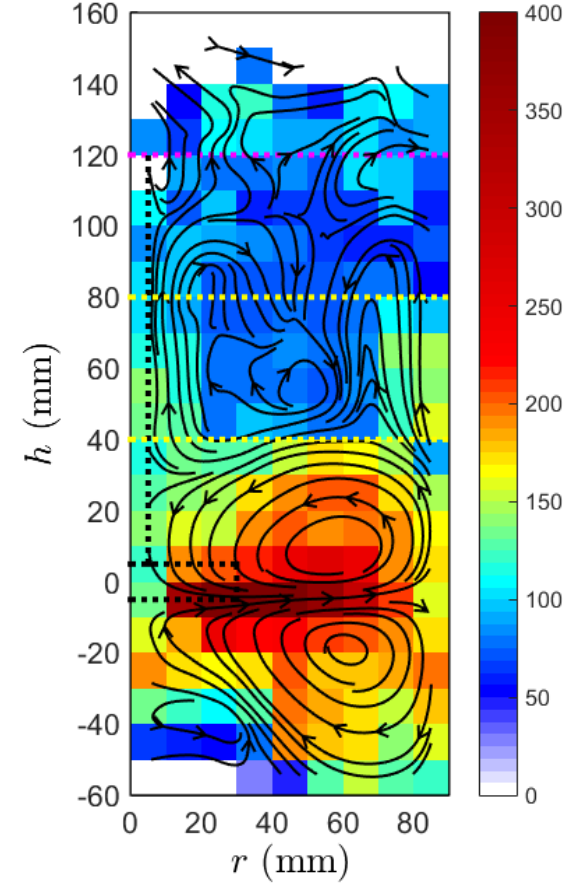
M1x4

Moderate levels of turbulence throughout the cell, relatively uniform in the upper mixing loop through the mesh and into the froth. Very different pattern to that experienced in other configurations



M3x4

Higher values of turbulence noted in the centre of the cell and by the cell wall in the mesh where the net flow is upwards. Very low turbulence in the centre of the mesh and the froth phase



M5x4

Figure 6.10 - Standard deviation of speed (mms^{-1}) per 10 mm^2 for the hydrophobic system, with the base case compared to the M1x4, M3x4 and M5x4 meshes in the vertical plane of the flotation cell. Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

High speeds of the tracer in the pulp up to the interface, with marginally lower velocities in the froth phase. Relatively fast overflowing behaviour

Turbulent in the pulp, with a sharp reduction in turbulence in the mesh and in the froth phase. The froth it turbulent above the lip of the cell

High levels of turbulence in the pulp within the mesh towards the wall of the flotation cell. Turbulence is high into the base of the froth. Low turbulence in the froth at the top of the froth, and in the mesh and froth in the centre of the cell

Turbulence profile similar to the M3xs4 mesh, slightly less turbulence against the cell wall in the mesh, with low turbulence in the froth. Froth above the cell lip is quite turbulent

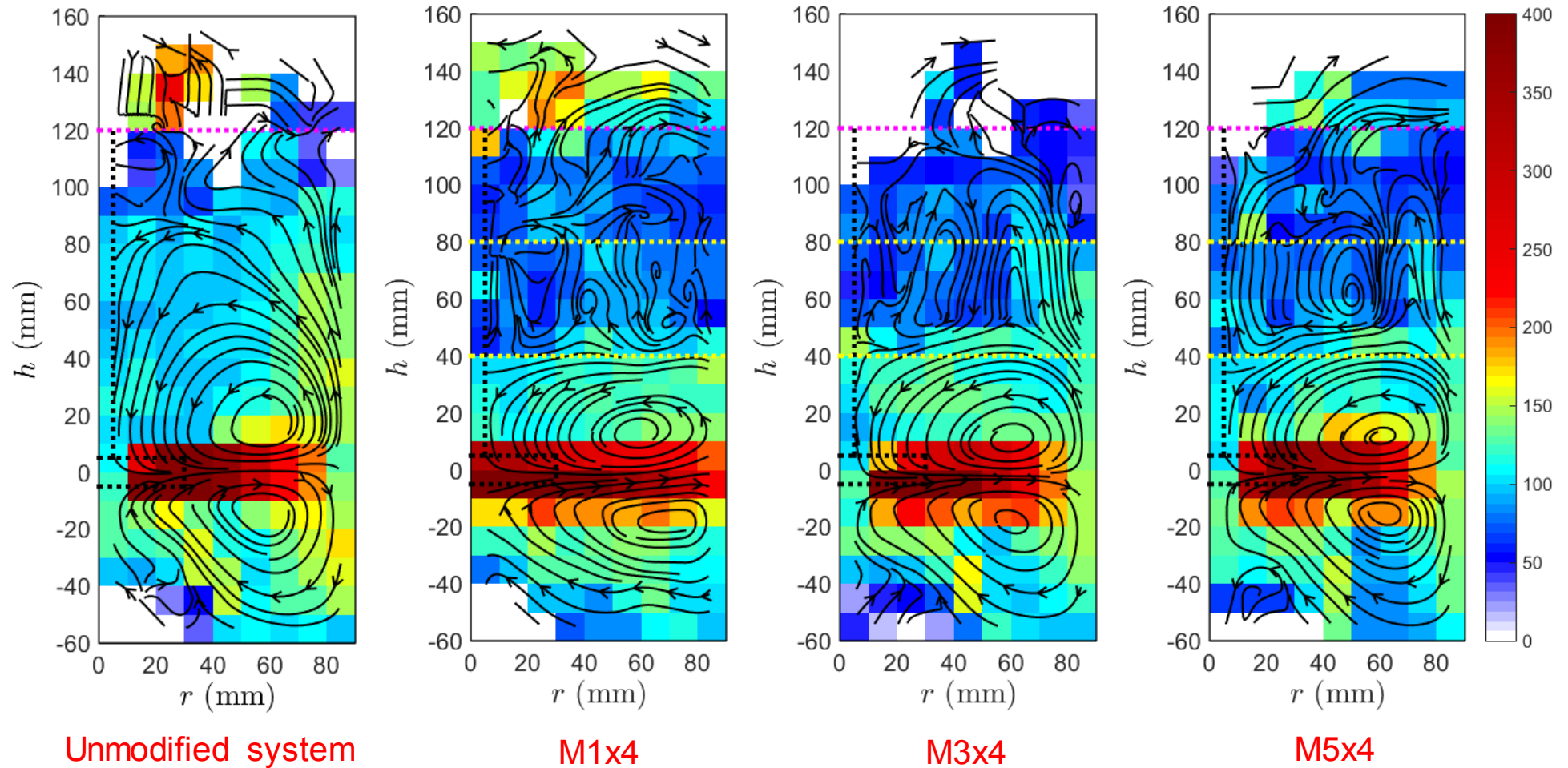


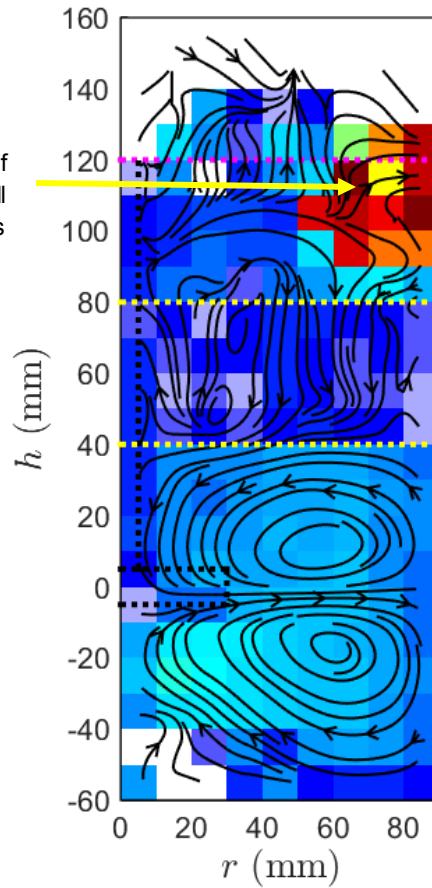
Figure 6.11 - Standard deviation of speed (mms⁻¹) per 10 mm² for the hydrophilic system, with the base case compared to the M1x4, M3x4 and M5x4 meshes in the vertical plane of the flotation. Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

Occupancy is low in the pulp phase, and very low in the mesh space. High occupancy of the tracer near the lip of the cell in the froth phase

High occupancy of the tracer in a very concentrated region close to the lip of the cell in the froth phase. Clear 'path' picked out through the mesh for the tracer by high occupancy results

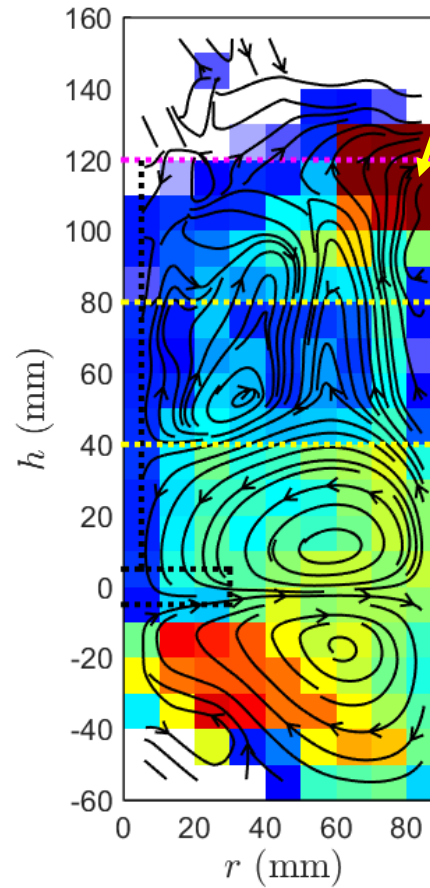
Tracer has very high occupancy in the centre of the mesh and throughout the vertical extent of the froth towards the lip of the cell. Tracer overflows infrequently. Very low occupancy in the mesh centre and edge where transport

Occupancy below the lip of the flotation cell up to 60 counts per 10 mm²



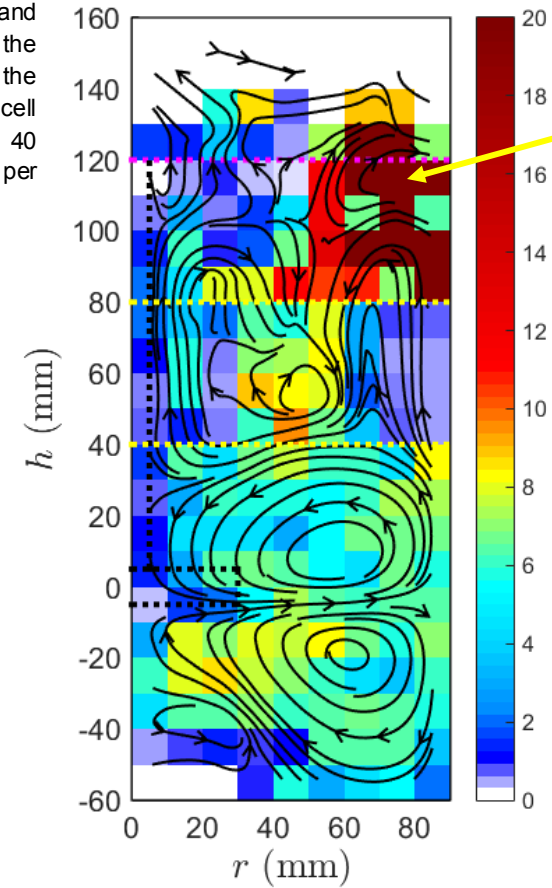
M1x4

Occupancy above and below the lip of the flotation cell up to 40 counts per 10 mm²



M3x4

Occupancy below the lip of the flotation cell up to 50 counts per 10 mm²



M5x4

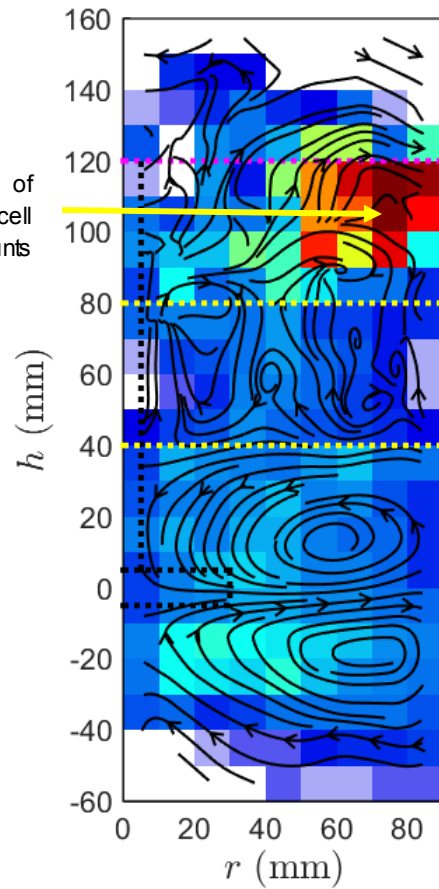
Figure 6.12 - Occupancy of the tracer per 10 mm² for the hydrophobic system, with the base case compared to the M1x4, M3x4 and M5x4 meshes in the vertical plane of the flotation cell. Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

Very low occupancy in the mesh, high occupancy in the froth close to the lip of the cell. Very similar profile to that of the hydrophobic tracer

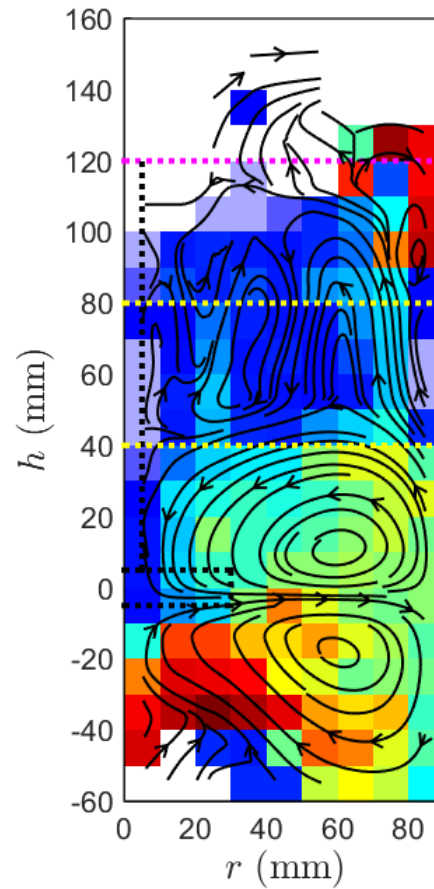
Low occupancy of the tracer in the mesh and in the froth. Relative to the hydrophobic tracer, moderately high occupancy of the tracer in the froth close to the lip of the flotation cell. High pulp occupancy of the tracer

Very high pulp occupancy of the hydrophilic tracer. Some occupancy in the centre of the mesh and at the base of the froth phase. However, occupancy is low in the upper portions of the froth close to the lip of the cell

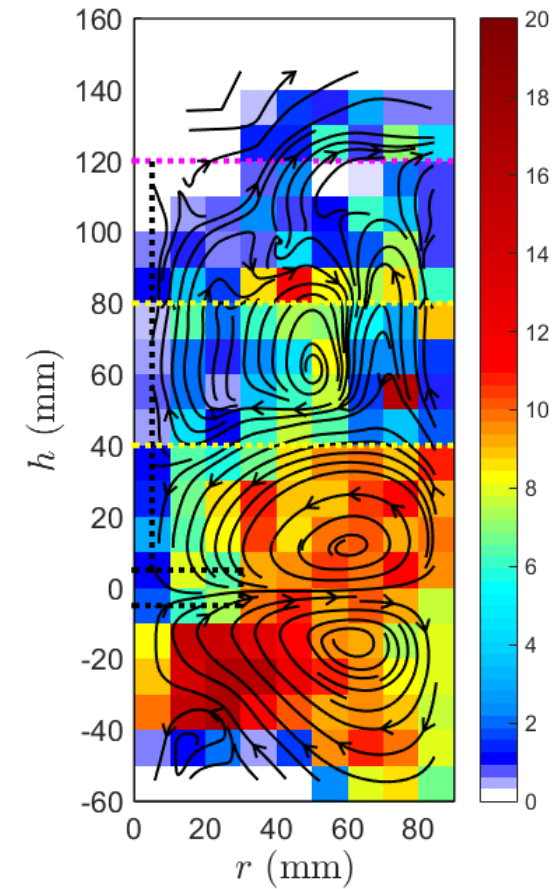
Occupancy below the lip of the flotation cell up to 60 counts per 10 mm²



M1x4



M3x4



M5x4

Figure 6.13 - Occupancy of the tracer per 10 mm² for the hydrophilic system, with the M1x4, M3x4 and M5x4 meshes compared in the vertical plane of the flotation cell. Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

6.4.2 Tracer behaviour with mesh hole-size

Figure 6.8 and Figure 6.9 display the hydrophobic and hydrophilic tracer speeds with respect to meshes of 40 mm thickness, and 10, 30 and 50 mm hole-size. It can be seen that the addition of a mesh results in an abrupt change in tracer speed in the vertical plane, relative to the more gradual change in speed from approximately 400 mms^{-1} to 100 mms^{-1} in the unmodified base case for the hydrophobic tracer, as shown in Figure 6.8. For the M1x4 mesh, speeds immediately drop to approximately 150 mms^{-1} within the mesh, from approximately 400 mms^{-1} in the mixing region below the mesh. Speeds are then consistent in the mesh and froth phase. For the M3x4 mesh, speeds decrease more gradually to approximately 200 mms^{-1} in the froth. Tracer speeds are particularly high in the mesh towards the edge of the cell. The M5x4 mesh results in high speeds towards the edge and centre of the cell, and a very low speed region in the centre of the mesh, corresponding to the down welling mixing region.

The hydrophilic tracer speed is faster as shown in Figure 6.9. This is particularly evident in the unmodified base case with tracer velocities in excess of 100 mms^{-1} greater than the hydrophobic tracer. The presence of the mesh, as with the hydrophobic tracer, results in a drop in tracer speed. However, tracer speeds remain relatively high towards the centre of the cell, and the reduction in tracer speed through the mesh is more diffuse. Tracer speeds are generally lowest towards the wall of the flotation cell.

The standard deviation of speed, representing indicative turbulence, is shown in Figure 6.10 and Figure 6.11 for the hydrophobic and hydrophilic tracers. As shown in Figure 6.10, Indicative turbulence is high in the unmodified base case, and the presence of the mesh significantly modifies the turbulence profile of both the hydrophobic and hydrophilic systems. The M1x4 mesh results in an immediate drop in indicative turbulence within the mesh and in the froth phase. The M3x4 mesh has a higher level of indicative turbulence within the mesh, but interestingly a drop in turbulence within the mixing region of the cell itself, relative to the unmodified base case. It also experiences the highest froth indicative turbulence of any of the designs. Within the M5x4 mesh, indicative turbulence is high near the cell wall and centre of the cell. In the centre of the mesh space, turbulence is low.

As shown in Figure 6.11, in contrast, the hydrophilic tracer shows less indicative turbulence under all configurations. The mesh, as with the hydrophobic tracer, reduces indicative turbulence within and above the mesh. In addition, the reduction in indicative turbulence is diffuse across a larger area in the cell when compared to the hydrophobic

system. Greater values of indicative turbulence are noted towards the edge of the cell for the tracers in all configurations. This dissipates quickly in the froth phase. High indicative turbulence is noted when the tracer enters the froth above the cell lip.

In terms of tracer occupancy, the mesh has an effect on the position of the tracer within the cell, for both the hydrophobic and hydrophilic systems, as indicated by Figure 6.12 and Figure 6.13 respectively. The unmodified base case is not shown due to data processing errors. A qualitative comparison can be found in Appendix C.

For the M1x4 configuration, there is very low occupancy of the tracer within the mesh itself. The tracer primarily occupies a region close to the cell lip. For the M3x4 mesh, the tracer is primarily present in a very concentrated region close to the cell lip. There are clear paths the tracer frequently follows through the mesh, 10-20 mm from the cell wall, showing high levels of occupancy. The majority of the hydrophobic tracer's movement is in a small region in the froth, close to the cell wall, and appears overflow immediately. The M5x4 mesh again shows a high (but more diffuse) occupancy of the tracer in the froth. However, the tracer has high occupancy in the centre of the mesh, being likely caught in the eddy that has formed there. The M5x4 mesh has a lower solids flowrate, and this is associated with the circulation of solids in the eddy at the centre of the mesh.

In contrast, the hydrophilic tracer shows variable occupancy in different regions of the cell with respect to the mesh hole-size. With the M1x4 mesh, the tracer has very low mesh occupancy but high occupancy below the lip of the flotation cell. In the M3x4 configuration, the tracer has a relatively high mixing phase occupancy, relatively low mesh occupancy (though higher than the M1x4 mesh), and some occupancy towards the lip of the flotation cell. The M5x4 mesh has very high occupancy in the mixing region of the pulp and within the centre of the mesh, and just above in the lower froth phase. There is, however, very low occupancy relative to the froth phase as observed in other configurations.

The effect of varying mesh hole-size on the behaviour of tracers is clear from the PEPT data. In the unmodified base case, there is a gradual reduction in tracer speeds and turbulence with increasing distance from the impeller to the pulp-froth interface, 80 mm above. There is low speed and turbulence in the froth below the lip, and generally increased indicative turbulence in the froth above the lip of the flotation cell. The hydrophobic tracer generally experiences increased indicative turbulence in the system relative to the hydrophilic, however the speeds of the tracer are similar in the pulp phase. Speeds in the froth for the hydrophobic tracer are greater than for the hydrophilic tracer,

whereas similar levels of turbulence are experienced for both. The addition of meshes results in a sharp reduction in both speed and turbulence across the mesh and into froth phase. However, how speed and turbulence respond across the mesh is different for each configuration. There is relatively uniform turbulence in the upper pulp and froth for the hydrophobic tracer in association with the M3x4 mesh, and the tracer is frequently entering the froth and overflowing. The M5x4 in particular displays behaviour detrimental to performance in the hydrophobic system, showing highly turbulent movement up through the mesh and the formation of an eddy, drawing solids into the mesh instead of allowing them to ascend into the froth.

The occupancy of the tracers is markedly different, with a tendency for the hydrophobic tracer to spend increasing time in the upper pulp and towards the lip of the cell in the froth. Occupancy in the mesh region is very low for the M1x4 and M3x4 meshes. The M1x4 hydrophobic and hydrophilic tracers show very high, similar occupancies across the pulp and froth. The implication is that the tracers are both being entrained, as the hydrophilic tracer cannot attach to bubbles. The M3x4 mesh results in a small region of very high occupancy of the tracer close to the cell wall and lip. High occupancy is also noted in the mesh directly below. The tracer appears to be directly moving from the mixing region in the pulp directly into the froth to overflow most frequently. The hydrophilic tracer shows increased occupancy in the froth in the M3x4 mesh near the lip, however, the number of locations is lower than that experienced by the hydrophobic tracer, implying that another mechanism, likely attachment is resulting in the tracer entering the froth with greater frequency. The M5x4 mesh results in the hydrophobic tracer occupying the lower froth with high very frequency, although the tracer does not often reach the lip of the cell. High occupancy is associated with the eddy in the centre of the mesh, the effect of which is negative. The hydrophilic tracer has poor froth occupancy in this configuration, again implying differing mechanisms for recovery, likely attachment for the hydrophobic tracer, and low levels of entrainment for both the hydrophobic and hydrophilic tracer.

These observations help to explain the solids flowrates observed in the factorial in Chapter 5. The mesh reduces indicative turbulence in the froth and upper pulp as shown in the figures, and in conjunction with a hole-size of 30 mm (M3x4 mesh), there is a statistically proven improvement in solids flowrate. The PEPT data is beneficial in understanding the effects of changes in mesh hole-size on the performance of the flotation system.

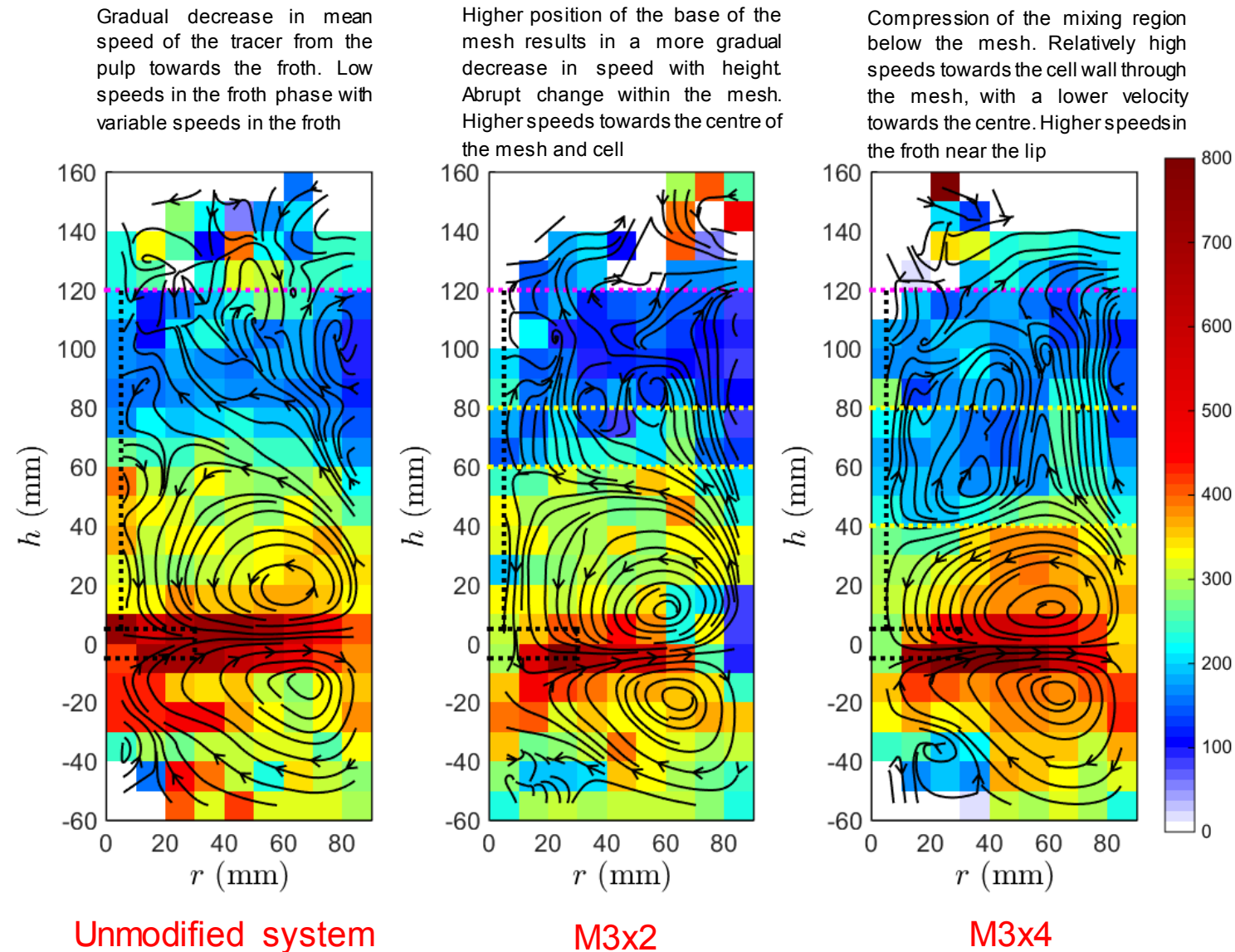


Figure 6.14 - Mean speed (mms^{-1}) per 10 mm^2 for the hydrophobic system, with the base case compared to the M3x2 and M3x4 meshes in the vertical plane of the flotation cell (effect of mesh position and thickness on mean speed). Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

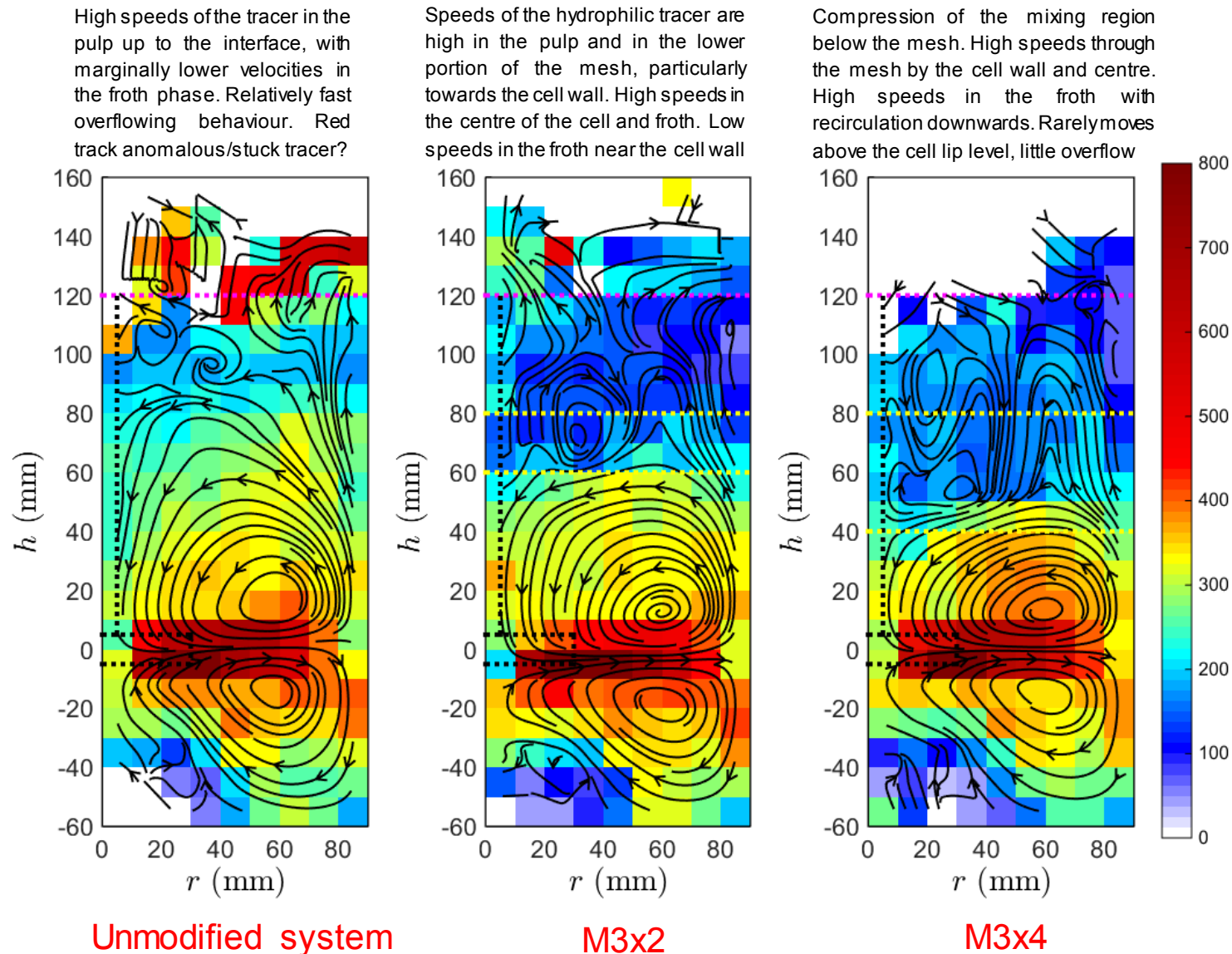


Figure 6.15 - Mean speed (mms^{-1}) per 10 mm^2 for the hydrophilic system, with the base case compared to the M3x2 and M3x4 meshes in the vertical plane of the flotation cell (effect of mesh position and thickness on mean speed). Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

Slow reduction in turbulence in the upper pulp and across the pulp – froth interface. Moderate turbulence in the froth above the lip of the flotation cell

Mesh reduces the turbulence experienced within and above it. Pockets of high turbulence in the mesh towards the wall of the flotation cell. Low turbulence in the froth

Moderate levels of turbulence throughout the cell, relatively uniform in the upper mixing loop through the mesh and into the froth. Very different pattern to that experienced in other configurations

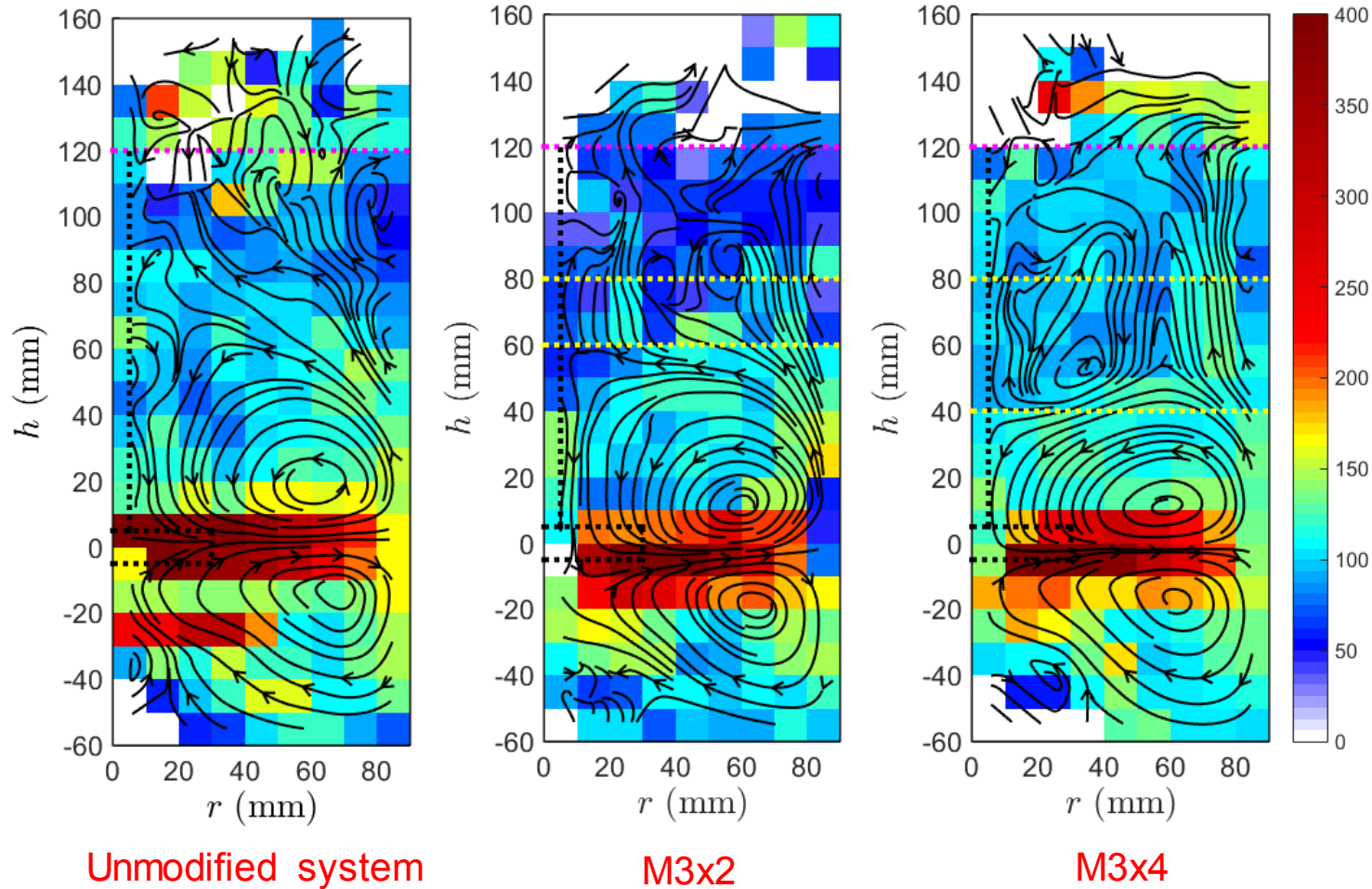


Figure 6.16 - Standard deviation of speed (mms⁻¹) per 10 mm² for the hydrophobic system, with the base case compared to the M3x2 and M3x4 meshes in the vertical plane of the flotation cell. Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

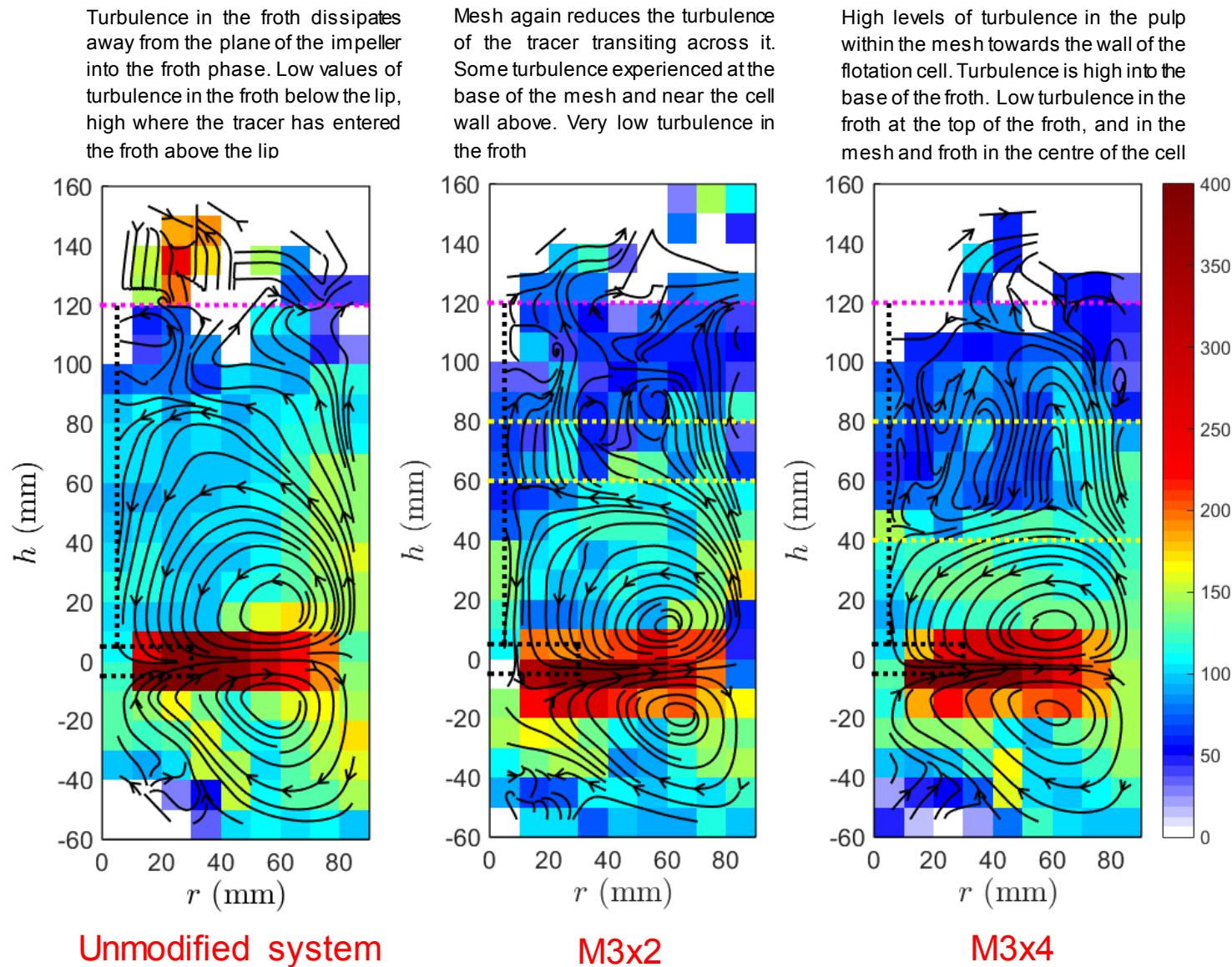
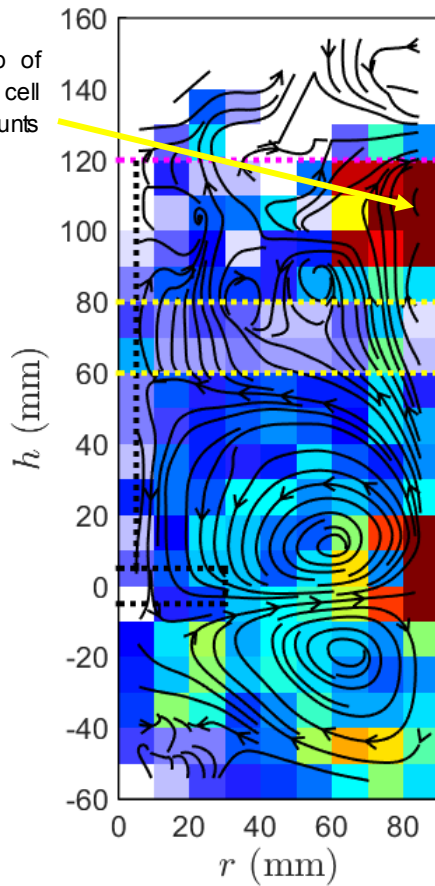


Figure 6.17 - Standard deviation of speed (mms^{-1}) per 10 mm^2 for the hydrophilic system, with the base case compared to the M3x2 and M3x4 meshes in the vertical plane of the flotation cell. Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

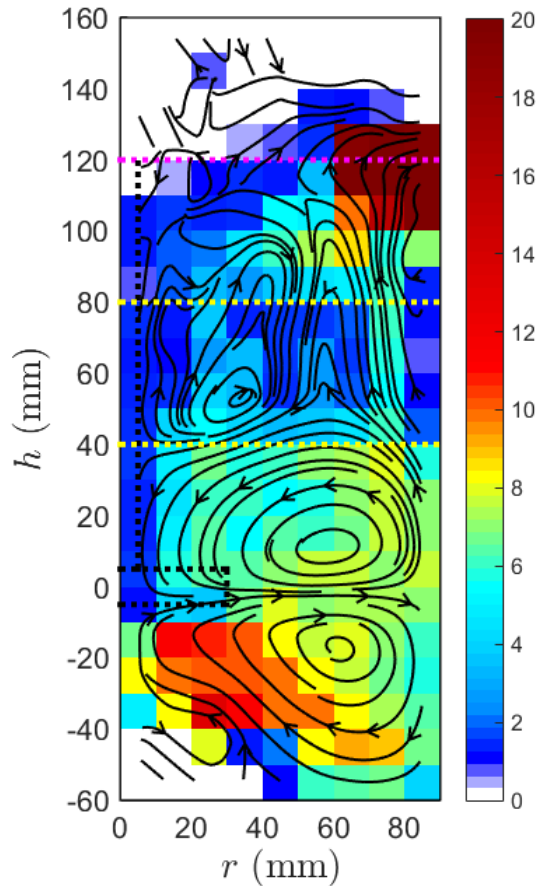
There is very low occupancy of the tracer in the mesh. Higher occupancy in the pulp below, and occupancy is concentrated towards the lip of the flotation cell. Tracer may have become stuck at the edge of the cell by the plane of the impeller

Occupancy below the lip of the flotation cell up to 40 counts per 10 mm²



M3x2

High occupancy of the tracer in a very concentrated region close to the lip of the cell in the froth phase. Clear 'path' picked out through the mesh for the tracer by high occupancy results



M3x4

Figure 6.18 - Occupancy of the tracer per 10 mm² for the hydrophobic system, with the M3x2 and M3x4 meshes compared in the vertical plane of the flotation cell. Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

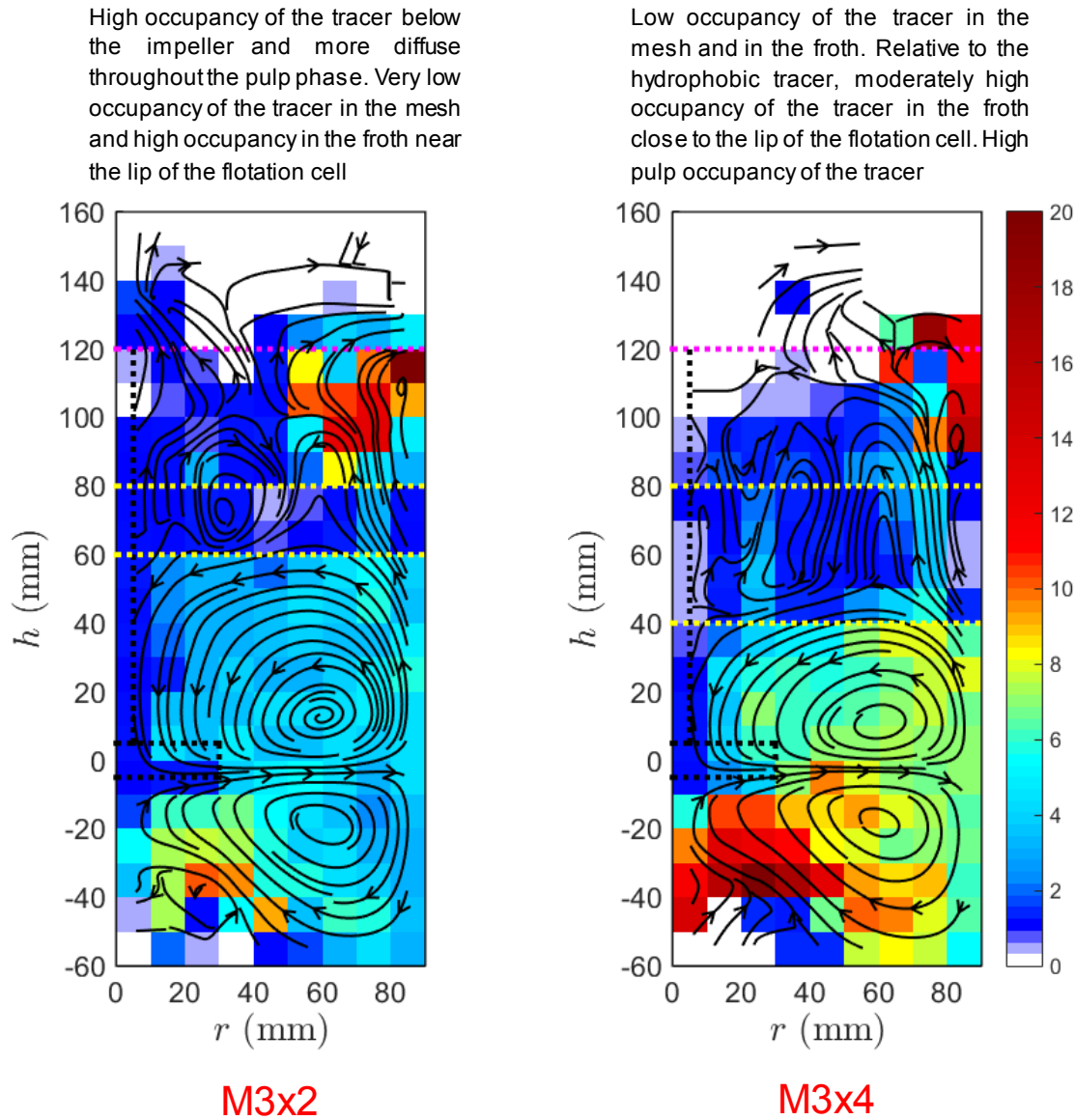


Figure 6.19 - Occupancy of the tracer per 10 mm² for the hydrophilic system, the M3x2, M3x2L and M3x4 meshes compared in the vertical plane of the flotation cell. Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

6.4.3 Tracer behaviour with mesh thickness

Observations have been made of the behaviour of the tracers with respect to mesh thickness changes. Figure 6.14 and Figure 6.15 indicate speed with respect to the hydrophobic and hydrophilic tracers for meshes with thicknesses of 20 and 40 mm with a 30 mm hole-size. The pulp phase occupies the same volume in the cell in both cases.

Comparing the M3x2 mesh with the unmodified base case in Figure 6.14 indicates they have a similar speed distribution in pulp phase. The mesh again acts as a barrier, and speed is reduced in the froth above. The M3x4 mesh is shown in comparison. As previously discussed, Speed is relatively higher through the mesh and in the froth above. Comparing speeds, as indicated in Figure 6.15 of the hydrophilic tracer, the speed of the

tracer is lower in the mixing region for all configurations. The mesh again acts to reduce the speed of the tracer.

The indicative turbulence is similar for both the hydrophobic and hydrophilic tracers on encountering and transiting through the meshes, as shown in Figure 6.16 and Figure 6.17. There is a reduction in indicative turbulence reduction across the M3x2 mesh from the pulp to the froth, with increased indicative turbulence towards the cell wall and low turbulence in the froth. In comparison, the M3x4 shows increased indicative turbulence across the mesh. The meshes are again shown to reduce indicative turbulence at the pulp-froth interface.

In terms of occupancy as shown in Figure 6.18 and Figure 6.19, both the hydrophobic and hydrophilic tracers experience very low occupancy in the mesh region. For the hydrophobic tracer in the M3x2 configuration, the tracer occupies the region close to the cell wall near the lip most often, and near the wall at the plane of the impeller, (this may be an anomaly). Similarly, for the M3x2 hydrophilic tracer, occupancy above the mesh in the froth below the cell lip is high. Tracer occupancy in the pulp is very high for the hydrophilic tracer relative to the hydrophobic tracer, and the M3x2 shows much reduced occupancy of the tracer in the froth relative to the M3x4 mesh.

An increase in the thickness of the mesh has an effect on the behaviour of both the hydrophobic and hydrophilic tracers. The M3x2 mesh results in increased occupancy of the tracer towards the cell wall, with moderately high speeds and reduced turbulence passing through the mesh. Recovery of solids from this configuration is relatively high in a particle-stabilised froth as shown in Chapter 5. The M3x4 mesh shown in comparison has the highest recovery of any configuration in Chapter 5, increased relative to the M3x2 and unmodified base case, and so increased thickness aids recovery of solids to the concentrate, through both entrainment or attachment, in association with increased liquid flowrates.

6.5 Tracer behaviour in the horizontal slice

Tracer behaviour in horizontal slices through the flotation cell with respect to mesh hole-size and thickness is discussed in this section.

6.5.1 Horizontal slices through the 40 mm thick meshes

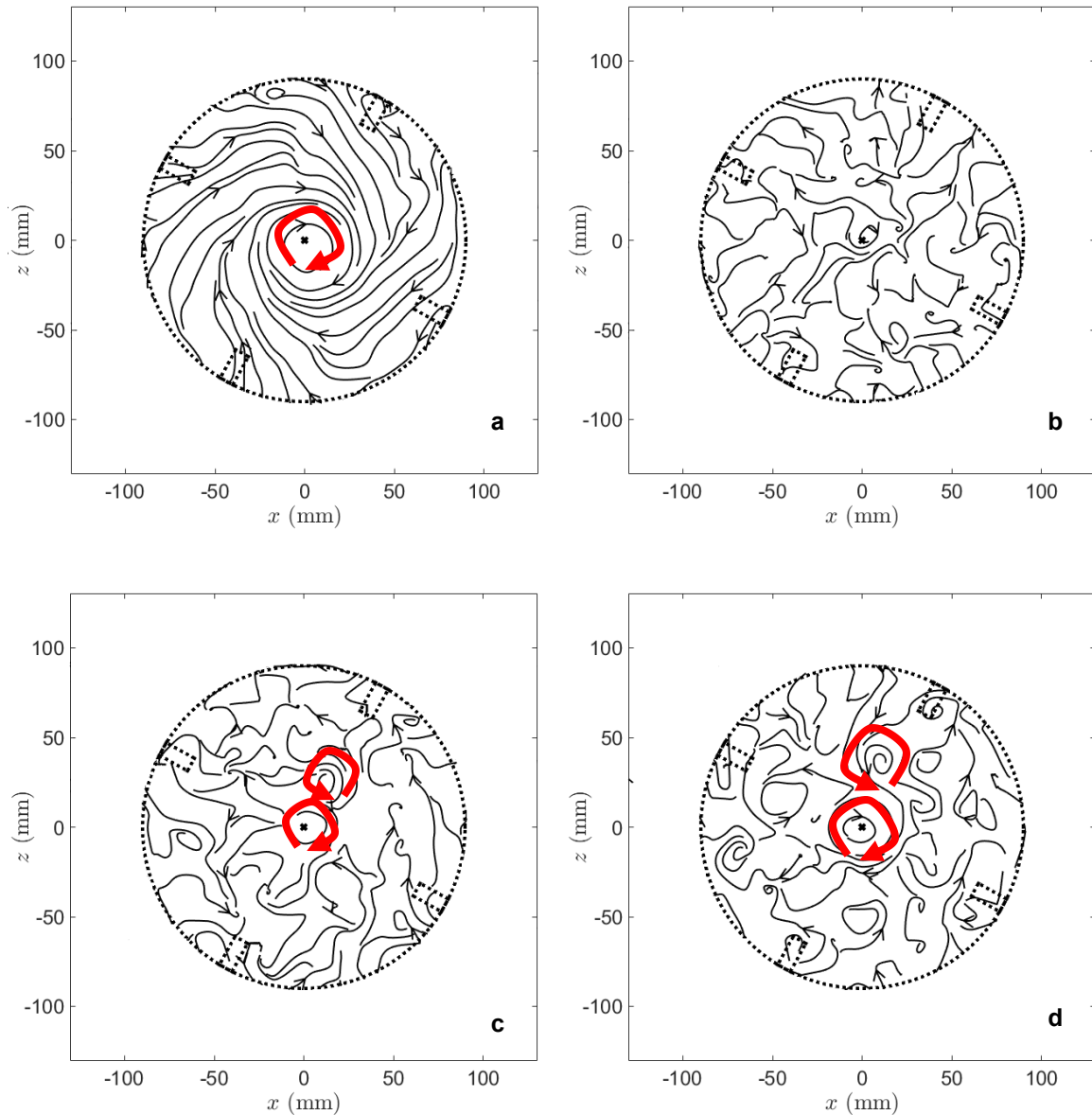


Figure 6.20 - Bulk flow of the tracer at 60 mm above the plane of the impeller for the unmodified base case (a), M1x4 Mesh (b), M3x4 (c) and M5x4 (d). Identifiable flow patterns are highlighted in red.

Figure 6.20 considers horizontal planes through the middle of the 40 mm thick meshes (60 mm above the plane of the impeller), in comparison to a plane through the unmodified base case at the same position. Swirl is visible, with an almost square clockwise rotation formed around the impeller shaft, with the tracer drawn into the centre of the cell. This is

evident in Figure 6.2, with a transition from a circular to a square rotation up from the plane of the impeller. All the designs break down the swirl below the pulp-froth interface.

The M1x4 mesh slice shows large, disordered motions, on the order of 50 mm in length. The hole-size of the mesh is 10 mm and therefore this is unrepresentative of the true motions of the tracer within the cell. The streamlines are averaging the movement of the tracer through the different holes in the mesh into single streamlines. In the case of the M1x4 mesh, the streamlines have lateral motions greater than the hole-size of the mesh which cannot be representative. The data resolution is not high enough to identify the true pattern of movement of the tracers through this mesh.

The horizontal plane through the M3x4 mesh results in a very distinct flow pattern. The swirl in the pulp is broken down by the presence of the mesh, and eddies form within the individual mesh holes. It can be seen that the mixing around the impeller is clockwise, whereas adjacent to this are anticlockwise flows, occupying spaces assumed to be the adjacent mesh holes. This is highlighted on Figure 6.20. In the next set of adjacent mesh holes, the flow appears to reverse again to clockwise. This behaviour remains unexplained.

The M5x4 mesh as shown in the figure also breaks down the swirl in the unmodified base case and results in large eddies as highlighted in red on the figure. Again the flow is clockwise around the impeller, counter clockwise in the adjacent mesh holes and then clockwise again towards the edge of the cell. These circulations are clearer with the M5x4 mesh, being easier to pick out due to their size.

The large eddies can be identified in the vertical slices shown in the previous figures for the M5x4 and M3x4 meshes. The eddies for the M5x4 meshes in particular are dominant in both the horizontal and vertical planes, drawing the tracer (and other particles) into the eddy and disrupting the froth stability above. By reducing the hole-size from 50 to 30 mm, there is still some downwards circulation in the centre of the mesh holes, but it appears to have a negligible effect on the occupancy of the tracer. As can be seen in the horizontal planes, small eddies form and there is a net upwards transfer of solids towards the edge of the mesh when considered with the horizontal slices. The net effect is positive for recovery of solids to the concentrate in a particle-stabilised system.

6.5.2 Horizontal slices through the 20 mm thick meshes

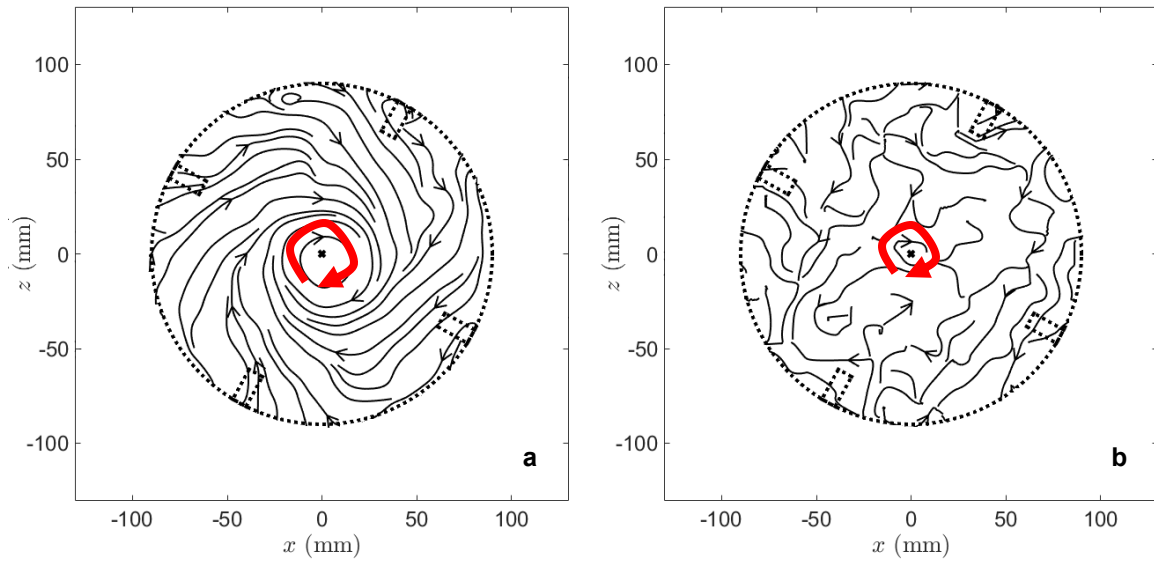


Figure 6.21 - Bulk flow of the tracer at 60 mm above the plane of the impeller for the unmodified base case (a) and 80 mm (top) of M3x2 mesh (b). Identifiable flow patterns are highlighted in red.

Figure 6.21 considers the effect of the thinner 20 mm mesh on the bulk flow within the cell. In Figure 6.21b, the M3x2 plane indicates bulk flow at the top of the mesh, just before the pulp-froth interface. It is clear that although eddies are beginning to form as with the M3x4 mesh, they are not as well developed and have larger lateral motions (perhaps representing the tracer being drawn into the mesh from the swirl below). It is clear that the swirl in the upper pulp is being broken down by the presence of the mesh.

6.6 A measure of turbulence, the particle Reynolds number

The tracer speed data for the hydrophobic and hydrophilic tracers made it possible to calculate an estimate of the particle Reynolds number, for a selection of mesh designs in comparison to the unmodified base case. The Reynolds number is a non-dimensional measure of turbulence for comparisons. The particle Reynolds number, Re_p , is defined as:

$$Re_p = \frac{vd\rho}{\mu} \quad (\text{Equation 6.1})$$

where v is the particle velocity, d is the particle diameter, ρ is the effective density of the bulk suspension (the pulp phase) and μ is the dynamic viscosity of the bulk mixture.

The effective density of the pulp phase, ρ_m , can be calculated using an equation proposed by Poletto (1995):

$$\rho_m = \rho_f(1 - \phi) + \rho_s \phi \quad (\text{Equation 6.2})$$

where ρ_f is the effective density of the fluid (for this case, water, 1000 kgm⁻³), ρ_s the density of the solid, 2500 kg m⁻³, and ϕ the solids fraction of the mixture by mass, 0.437. The resultant effective density is 1655.5 kgm⁻³ for the pulp phase.

The dynamic viscosity, μ_m , is determined from the equation first presented by Thomas (1965):

$$\mu_m = \mu_f(1 + 2.5\phi + 10.05\phi^2) \quad (\text{Equation 6.3})$$

where μ_f is the viscosity of the fluid, 0.001 Pas and ϕ the solids fraction of the mixture by mass, 0.437. The resultant dynamic viscosity is 4.0117x10⁻³ Pas.

For comparison, the particle Reynolds number was calculated using the above values and Equation 6.1 for the unmodified base case, the M3x4 mesh and the M5x4 mesh, at the centre of the mesh and 10 mm from the lip of the cell. In all cases the measurement is at 60 mm above the plane of the impeller. These values are displayed in Table 6.2.

Table 6.2 - Particle Reynolds number for three different configurations in the plane of the mesh

Design	Tracer type	Tracer diameter (µm)	Tracer speed, centre of mesh (45 mm from cell wall), ms ⁻¹	Tracer speed, 10 mm from cell wall, ms ⁻¹	Particle Reynolds number (45 mm from the cell wall)	Particle Reynolds number (10 mm from cell wall)
Unmodified base case	Hydrophobic	575	0.2894	0.3079	690.846	735.039
Unmodified base case	Hydrophilic	500	0.3074	0.3233	638.167	671.020
M3x4	Hydrophobic	435	0.1759	0.2442	317.605	441.096
M3x4	Hydrophilic	530	0.1817	0.2148	399.894	472.533
M5x4	Hydrophobic	575	0.1595	0.2468	380.796	589.136
M5x4	Hydrophilic	460	0.2026	0.1820	386.997	347.556

It can be seen from the table that the particle Reynolds number drops substantially for the M3x4 and M5x4 mesh at the mid-point between the centre of the cell and the cell wall compared to the unmodified base case. There is also a drop in the particle Reynolds number, but to a lesser degree closer to the cell wall for both meshes in comparison with the unmodified base case. There is some difference between the hydrophobic and hydrophilic Reynolds numbers which may be explained by the range of trace dimensions.

The reduction in the speed of the tracer in the region of the mesh results in a much reduced Reynolds number. There is less turbulence occurring in the region with a mesh modification in place, as originally conceptualised.

6.7 Chapter conclusions

The PEPT experiments have proved to be instrumental in gaining an understanding into the effect of variable mesh hole-size and thickness on particle behaviour. The effect of swirl on the pulp phase was demonstrated for the first time, with the condition persisting up to the pulp-froth interface. The addition of the mesh breaks down the swirl, affecting turbulence, and results in axial flow of the tracers into the froth.

The PEPT data indicates why there is an optimum hole-size, 30 mm, among the meshes tested. At this size there is a higher solids flowrate than for design without modification (as indicated in Chapter 5), and the bulk flow across the mesh actively transports solid and liquid upwards into the froth with little net downwards flow. A small mesh hole-size 10 mm prevents the transport of particle-stabilised bubbles into the froth phase. The tracer was most likely entrained into the froth, and this is observed in the PEPT data. The largest hole-size, 50 mm, results in large eddies within the holes of the mesh, which are destructive at the pulp-froth interface, and draw back solids. This reduces the solids flowrate of the associated froth.

As observed in Chapter 5, increasing mesh hole-size resulted in a statistically significant variability in flotation performance. The PEPT data in both the horizontal and vertical planes has indicated very different tracer behaviours with respect to each hole-size, which help to explain the differences observed in performance. The PEPT data indicates the 30 mm hole-size optimises pathways for solids to be recovered to the concentrate, which correlates well with the significantly higher flowrates observed with the M3x4 mesh, relative to the unmodified base case in Chapter 5.

Thickness also appears to have an effect on tracer behaviour, the hydrophobic tracer in particular. The thicker 40 mm mesh reduces the size of the upper mixing loop in the pulp phase, increasing speed and turbulence in the pulp below, and allows for a more direct transfer of the tracers into the froth. This is particularly evident with the occupancy of the M3x4 hydrophobic tracer, with a clear identifiable path through the mesh. The hydrophilic tracer enters the froth more frequently with increased thickness, as entrainment is directly

associated with increased liquid flowrate. The hydrophobic tracer is likely to be entrained more frequently as well.

A thinner mesh of 20 mm with a hole-size of 30 mm is shown to have increased solids flowrates relative to the unmodified base case in Chapter 5, as well as increased liquid flowrates. The thinner mesh, sitting just under the froth has smaller eddies in the mesh holes. It also directs the tracer straight into the froth, rather than the longer pathway observed in the unmodified base case.

As indicated in Chapter 5, the M3x4 mesh shows a statistically significant improvement in solids flowrate relative to the unmodified base case. The combination of increased mesh thickness at 40 mm, with a mesh hole-size of 30 mm, results in the greatest number of pathways for the tracers to enter the froth, and very high occupancy of the tracers near the lip of the cell. This can be correlated with the experimental results in Chapter 5, indicating high solids flowrate for this configuration. Increased liquid flowrates are associated with the meshes, resulting in increased entrainment of the tracers (and particles) into the concentrate.

The horizontal slices through the flotation cell have for the first time, demonstrated swirling of the tracer in the bulk flow around the impeller. The swirl is circular at the base of the flotation cell underneath the impeller. The swirl becomes square in form above the impeller and persists up to the pulp-froth interface. This indicates the region below the froth is turbulent in nature, and likely resulting in particle detachment into the pulp phase. The presence of the meshes breaks down this swirl and is replaced with axial flow, with the tracer and particles entering the froth directly from below in the pulp. Turbulence at the pulp-froth interface is reduced to differing degrees, depending on the configuration. This observation is confirmed by the Reynolds numbers derived from the tracer speed data. Where turbulence remains broadly similar in some cases, the pathways indicated by the tracer are much shorter from the pulp into the froth and encounter higher upward speeds and low occupancy, implying the tracer rapidly enters the froth.

It is clear from the PEPT data that the effect of mesh hole-size and thickness on tracer behaviour has been determined and it can be seen that the M3x4 mesh delivers an optimal configuration for hydrophobic tracer recovery to the concentrate.

Chapter 7

Conclusions and Further Work

7.1 Conclusions

The aim of this thesis was to understand some of the fundamental processes which govern flotation behaviour, and attempt to improve operational performance through mitigating against detrimental effects.

A novel 4 L bench-scale continuously recycling flotation system was devised in order to study flotation performance at steady state. An initial study of particle size effects on froth stability determined that with a decrease in particle size, there was an associated increase in air recovery, solids and liquid flowrates. Where air recovery falls below 50 % for a range of superficial gas velocities, the peak in air recovery corresponds to the peak in solids flowrate. High liquid content in froths may have an additional stabilising effect on the froth phase.

A PEPT investigation into particle behaviours in this unmodified system determined that swirl in the pulp phase persisted into the lower froth. This turbulent effect was likely to be highly detrimental to the recovery of particles to the froth phase. A potential solution was based upon a study by Zhang et al. (2009), where laminar axial flow of particles was generated through the addition of a horizontal mesh across a flotation column, improving recovery.

A full three-way experimental factorial was devised, based upon a horizontal mesh of varying hole-size and thickness. The result of this investigation was a mesh of 30 mm hole-size and 40 mm thickness resulting in an increased solids flowrate, or indicative

recovery to the concentrate. This result was statistically validated with respect to the unmodified base case.

A further PEPT investigation of particle behaviours, with a selection of the meshes tested, revealed that the meshes prevented swirl from affecting the froth phase, leading to axial flow of tracers into the froth. Turbulence is reduced, as indicated by the derived Reynolds numbers across the meshes in comparison with the unmodified base case. A mesh hole-size of 30 mm resulted in the greatest number of pathways for tracers into the froth phase, with a mesh thickness of 40 mm resulting in the tracers entering the froth with increased frequency. This correlates well with the increased recovery as determined by the experimental factorial.

This thesis has set the groundwork to improving recovery in flotation through the addition of a mesh to the flotation cell, the effects of which have been statistically validated, and quantitatively observed with PEPT.

7.2 Further work

This thesis presented results produced during the course of this PhD. The potential scope of this project was much greater, the effects of the meshes on the recovery of different particle size distributions for example. Some further preliminary work had been undertaken, including tests of refined mesh designs. The experimental system is very versatile however, and potential further work is outlined here.

7.2.1 The effect of particle shape

We have seen the effect of particle size on air recovery and performance. However, this system made use of spherical ballotini, which are not representative of a true ore system. It is proposed to replace the spherical ballotini with glass flakes, with a comparative investigation run to see what effects changing the particle shape has on air recovery and flotation performance. This would be more informative in terms of the behaviour of particles in a true industrial float.

7.2.2 A true flotation separation (two species system)

The current experimental system is single species. This allows us to study fundamental processes, with suitable proxies available for grade and recovery. However, in reality, flotation is an active separation of one mineral from a host ore, which may comprise many

other mineral types. Studying a true separation would give us accurate grade and recovery measurements, as well as allow us to study entrainment. How these values are affected by changes to the experimental parameters such as J_g and particle size distribution could be determined. This is with a view to optimising grade and recovery on plant through adjusting operational conditions to suit the feed distribution and proportions of mineral to gangue in the feed.

7.2.3 Refined mesh designs

The mesh designs have had a varied impact on flotation performance. The PEPT investigation has highlighted issues with the mesh designs. It is possible to continue to refine the designs to potentially simplify the designs and improve performance further, particularly in terms of recovery. Some initial work has been outlined in Appendix B.

7.2.4 PEPT experimental system improvements

The current PEPT experimental system has a very high liquid content. There is markedly different behaviour in terms of the hydrophobic and hydrophilic tracers, but it cannot be assumed that the hydrophobic tracer is attached to bubbles, particularly in the froth phase. Development of a particle-stabilised system for PEPT would go some way to alleviating concerns about particle behaviours. A particle-stabilised froth would have differing properties from a liquid stabilised one, and therefore there would be new insights and results to be gained from changing the experimental system.

Chapter 8

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Appendix A

Data tables

Listed in this Appendix is the raw manually recorded data for each of the experiments undertaken during the course of this PhD.

Table A.1 - Particle size data table (Chapter 4)

PSD	Jg (cms ⁻¹)	Solids flowrate (gs ⁻¹)	Liquid flowrate (gs ⁻¹)	Air recovery (%)	Solids percent in concentrate
Fine	0.66	4.72	1.28	23.16	78.67
Fine	0.98	6.84	3.30	32.91	67.46
Fine	1.31	10.89	9.15	61.45	54.34
Fine	1.31	9.99	9.90	67.38	50.23
Fine	1.64	8.70	16.83	85.18	34.09
Fine	1.97	9.02	20.34	90.39	30.72
Fine	0.66	5.93	1.43	30.19	80.57
Fine	0.98	7.11	3.38	43.58	67.78
Fine	1.31	10.19	7.95	85.67	56.16
Fine	1.31	9.62	8.82	55.78	52.16
Fine	1.64	8.85	11.52	76.30	43.44
Fine	1.97	6.37	17.12	72.41	27.11
Fine	0.66	4.76	1.60	33.50	74.84
Fine	0.98	5.67	3.25	52.31	63.56
Fine	1.31	8.93	8.25	67.75	51.97
Fine	1.64	7.70	14.62	70.75	34.50
Fine	1.97	7.29	16.74	67.41	30.34
Intermediate	0.66	5.80	2.60	39.45	69.05
Intermediate	0.98	8.61	4.62	56.92	65.08
Intermediate	1.31	6.92	6.50	50.07	51.55
Intermediate	1.31	7.92	7.28	56.23	52.12
Intermediate	1.64	6.22	11.68	60.98	34.76
Intermediate	1.97	5.38	16.83	65.87	24.23
Intermediate	0.66	3.55	0.48	35.05	88.08
Intermediate	0.98	5.60	3.50	44.71	61.54
Intermediate	1.31	7.99	5.64	54.47	58.63

Intermediate	1.31	9.10	6.86	64.78	57.02
Intermediate	1.64	7.77	9.94	75.32	43.87
Intermediate	1.97	6.57	13.72	62.79	32.37
Intermediate	0.66	5.40	2.24	35.43	70.70
Intermediate	0.98	7.07	3.43	45.27	67.33
Intermediate	1.31	8.93	6.60	51.58	57.49
Intermediate	1.31	7.56	6.86	51.34	52.43
Intermediate	1.64	7.68	12.50	74.95	38.08
Intermediate	1.97	6.32	18.63	70.37	25.32
Coarse	0.66	3.61	1.32	27.63	73.24
Coarse	0.98	4.57	2.04	37.89	69.15
Coarse	1.31	9.18	4.32	43.72	68.00
Coarse	1.64	7.73	7.89	38.75	49.51
Coarse	1.97	6.76	10.74	32.31	38.65
Coarse	0.66	3.89	1.38	24.33	73.80
Coarse	0.98	5.10	2.24	25.01	69.47
Coarse	1.31	8.67	3.76	44.93	69.76
Coarse	1.64	7.62	6.24	28.32	54.97
Coarse	1.97	6.64	12.60	29.83	34.52
Coarse	0.66	3.86	1.56	26.93	71.24
Coarse	0.98	5.00	1.62	28.91	75.54
Coarse	1.31	9.33	4.85	41.96	65.82
Coarse	1.64	7.71	9.60	41.44	44.57
Coarse	1.97	4.90	13.59	42.88	26.52

Table A.2 - ANOVA data table (Chapter 5)

Mesh hole-size (mm)	Mesh thickness (mm)	Jg (cms ⁻¹)	Solids flowrate (gs ⁻¹)	Liquid flowrate (gs ⁻¹)	Air recovery (%)	Solids percent in concentrate
30	40	1.31	10.32	10.00	62.94	50.79
30	40	1.64	6.73	10.71	74.33	38.60
30	40	0.98	9.32	5.00	29.07	65.08
30	40	1.31	7.87	8.26	59.45	48.78
30	40	1.31	11.10	8.20	78.99	57.51
30	40	0.98	6.57	5.10	57.64	56.30
30	40	1.64	6.68	11.76	64.72	36.22
30	40	1.31	11.60	10.00	72.34	53.70
30	40	1.31	12.70	10.40	70.72	54.98
30	40	0.98	5.13	3.60	46.52	58.75
30	40	1.64	7.94	12.60	65.33	38.65
30	40	1.31	11.92	12.60	59.98	48.61
30	30	1.31	8.94	5.60	56.17	61.49
30	30	1.64	5.60	8.19	56.51	40.61
30	30	0.98	3.41	2.28	33.31	59.92
30	30	1.31	9.46	7.90	42.32	54.49
30	30	1.31	13.10	8.70	71.79	60.09
30	30	1.31	7.60	6.50	58.53	53.90

30	30	0.98	2.95	3.04	41.05	49.27
30	30	1.64	5.18	8.40	58.41	38.14
30	30	1.31	7.36	8.60	60.03	46.12
30	20	1.31	8.72	5.20	57.20	62.64
30	20	1.64	6.10	7.54	48.65	44.71
30	20	0.98	5.90	3.38	30.45	63.61
30	20	1.31	9.42	8.40	58.90	52.86
30	20	1.31	7.32	3.40	46.11	68.28
30	20	0.98	3.53	1.05	10.58	77.07
30	20	1.64	4.76	7.44	44.87	39.04
30	20	1.31	7.60	5.00	51.81	60.32
20	20	1.31	8.78	7.20	51.74	54.94
20	20	1.64	4.63	11.40	28.43	28.89
20	20	0.98	5.22	3.42	52.54	60.42
20	20	1.31	8.50	9.80	59.42	46.45
20	20	1.31	5.50	4.14	56.90	57.04
20	20	1.64	5.11	6.06	40.18	45.76
20	20	0.98	3.64	2.40	35.93	60.24
20	20	1.31	10.04	8.20	53.32	55.04
50	20	1.31	4.90	4.80	33.16	50.52
50	20	0.98	0.41	0.24	16.97	63.22
50	20	1.64	2.59	7.28	29.62	26.26
50	20	1.31	3.66	4.05	29.86	47.49
40	20	1.31	4.70	2.60	8.90	64.38
40	20	1.64	2.44	5.76	32.02	29.76
40	20	1.31	4.84	3.80	15.80	56.02
40	20	1.31	2.24	2.40	30.32	48.28
40	20	0.98	1.14	0.76	16.82	59.92
40	20	1.64	2.06	5.68	39.51	26.58
40	20	1.31	2.52	2.88	15.84	46.67
50	40	1.31	7.07	7.47	58.61	48.61
50	40	1.64	5.30	11.07	63.65	32.38
50	40	0.98	4.55	3.24	36.02	58.40
50	40	1.31	7.29	10.70	72.85	40.52
50	40	1.31	4.95	5.00	63.65	49.75
50	40	0.98	4.15	2.59	42.99	61.58
50	20	1.64	4.17	6.49	52.04	39.11
50	20	1.31	4.80	5.50	56.58	46.58
50	30	1.31	5.60	3.84	55.37	59.34
50	30	1.64	4.57	8.20	42.79	35.79
40	20	0.98	2.83	2.00	22.16	58.55
40	20	1.31	5.27	6.70	58.33	44.03
40	40	1.31	2.09	4.86	26.55	30.11
40	40	0.98	1.17	0.93	12.38	55.65
40	40	1.64	2.01	8.89	19.51	18.43
40	40	1.31	2.56	6.65	26.15	27.76
40	30	1.31	3.04	2.49	30.00	55.01
40	30	1.64	2.94	7.14	31.86	29.17
40	30	0.98	1.65	1.05	13.79	61.11
40	30	1.31	4.32	5.60	41.23	43.55

20	30	1.31	5.26	8.03	63.11	39.57
20	30	1.64	4.14	13.75	75.62	23.12
20	30	0.98	3.98	3.85	35.92	50.81
20	30	1.31	5.12	10.67	53.38	32.40
20	40	1.31	4.86	9.18	55.67	34.62
20	40	1.31	6.20	6.90	60.72	47.33
20	40	0.98	4.19	3.12	26.66	57.31
20	40	1.64	5.83	14.76	71.32	28.32
20	40	1.31	7.15	9.90	82.45	41.94

Appendix B

Additional mesh tests

B.1 Further mesh improvement tests

After the completion of the experimental factorial and associated statistical analysis, it was decided to refine the mesh and see if it resulted in any further improvement in performance. Two modifications to the basic design were tested and the results presented below.

B.2 Mesh design changes

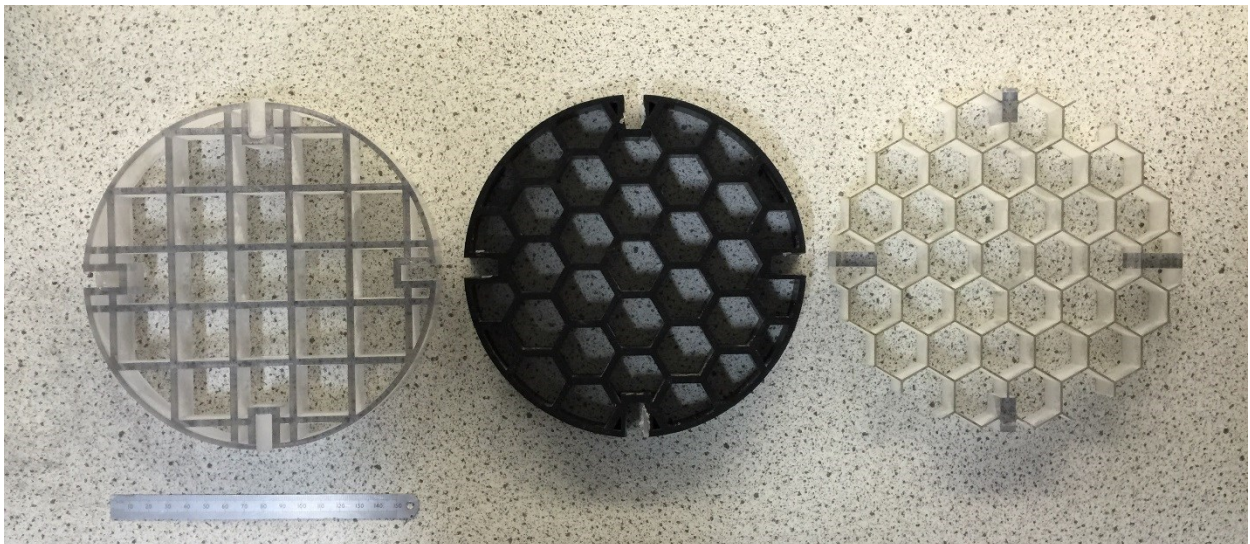


Figure B.1 - The three mesh designs tested. Square mesh, standard M3x2 and a thin walled mesh

For the modification tests, one prior tested mesh design was used as a reference point, the M3x2 mesh, sitting 40 mm below the lip of the cell at the pulp-froth interface. Two

modifications to the standard design were chosen. All three designs are shown for comparison in Figure B.1.

It was decided to change the shape of the mesh-hole from a hexagon to a square. This was chosen with manufacturing ease in mind. In the original hexagon, the greatest diameter between any vertices was 20 mm. This was maintained at 20 mm in the square mesh.

Secondly, the refinement of the original M3x2 hexagonal mesh was chosen. In this case, the walls of the mesh were thinned down to their minimum printable size 1 mm. The rim running around the edge of the mesh was also removed, leaving the sides of the hexagons to abut the walls of the flotation cell. This was decided as it was perceived that an edge to the mesh and thick mesh walls may be a barrier to the transport of material across it.

B.3 Experimental procedure

For these tests, the experimental set-up and procedure was to be the same as that undertaken for the experimental factorial. 900 g of 40 - 150 μm ballotini were run with 2.9 L of deionized water, with 1.2 mL of 2 mM TTAB solution and 10 mL 0.1 M MIBC solution. The experiment conditioned for 45 minutes without air and 15 minutes with air. Dosing of MIBC began at a rate of 4.2 mlh^{-1} . Results were then recorded across three superficial gas velocities. Air recovery and concentrate flowrates were measured and recorded. Each mesh was repeated three times and the results averaged and compared below.

B.4 Results and discussion

Presented in Figure B.2 below are the results of the experiments.

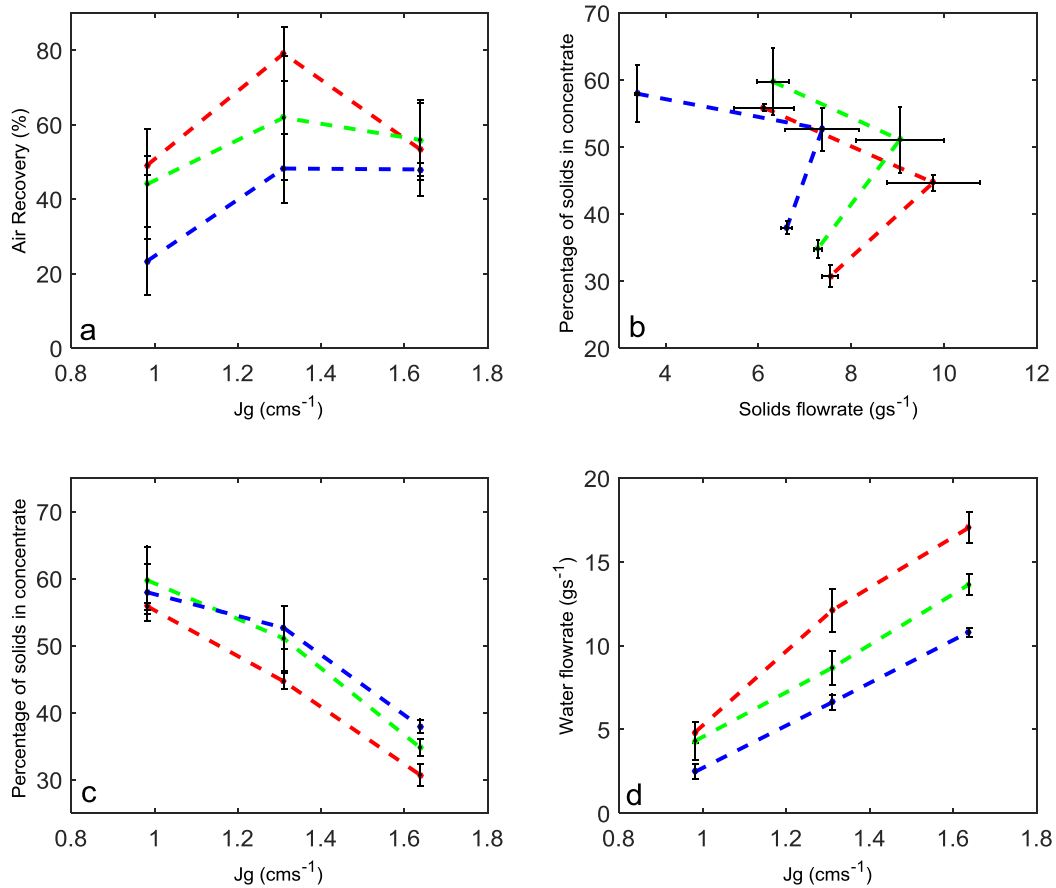


Figure B.2 - Air recovery (a), solids flowrate with percentage solids in concentrate ('recovery' versus 'grade') (b), percentage of solids in concentrate (c) and water flowrate (d) for three different mesh designs

Figure B.2 describes the effects of changing the mesh design. In green, the standard mesh configuration chosen, the M3x2, is presented. In red, the thin walled M3x2 mesh, and in blue, the square mesh.

Firstly, considering air recovery, we see that the unmodified design has an air recovery of 44 % at a Jg of 0.98 cms⁻¹, before increasing to a peak air recovery of 61.85 % at a Jg of 1.31 cms⁻¹. This is followed by a reduction at a Jg of 1.64 cms⁻¹ of 55.9%. The square mesh has a reduced air recovery in compared to the hexagonal mesh, with air recovery at a Jg of 0.98 cms⁻¹ of 23.38 %, followed by an increase at a Jg of 1.31 cms⁻¹ to 48.19%, before an almost identical air recovery of 47.96 % is recorded at a Jg of 1.64 cms⁻¹. Conversely, the thin walled mesh records improved air recoveries, starting with an air

recovery of 49.13 %, before increasing significantly to an air recovery of 79.06 % at a Jg of 1.31 cms^{-1} . At a Jg of 1.64 cms^{-1} , air recovery falls to 53.4 %.

These results suggest the thin walled mesh improved performance, with a square mesh being the worst performer. Considering the indicative grade-recovery curves in the figure, it can be seen that with respect to solids flowrates, the square mesh is the worst performer, with the standard M3x2 mesh providing intermediate performance and the thin walled mesh generating the highest solids flowrates. The data is presented as a function of percentage of solids by mass in the concentrate. Jg's correspond to each of the plotted points, with the point in the top left of each design tested representing a Jg of 0.98 cms^{-1} , followed by a Jg of 1.31 cms^{-1} and finally a Jg of 1.64 cms^{-1} . Examining the data, it can be seen that all three systems have a peak in solids recovery at the intermediate Jg value of 1.31 cms^{-1} . This corresponds to the peak in air recovery for each of the designs tested. The square mesh peaks at a solids flowrate of 7.39 gs^{-1} , the standard M3x2 mesh peaks at a flowrate of 9.05 gs^{-1} , and the thin walled mesh peaks at a flowrate of 9.77 gs^{-1} . The standard and thin walled mesh flowrates are within the error of each other however, so potentially there may not be a significant difference in their respective behaviours.

Secondly, it is notable that with an increase in the solids flowrate of each experiment, there is a subsequent reduction in the proportion of solids in the froth phase. This is evident not only in the indicative grade-recovery curve graph, but the percentage of solids in concentrate by mass graph, with respect to Jg. The square and standard M3x2 mesh follow similar profiles in terms of solids content, with an initial starting value of $\sim 60 \%$ for a Jg of 0.98 cms^{-1} , before reducing to $\sim 55 \%$ at a Jg of 1.31 cms^{-1} , before reducing to $\sim 40 \%$ at a Jg of 1.64 cms^{-1} . The thin walled mesh however, starts at $\sim 55 \%$ at a Jg of 0.98 cms^{-1} , before reducing to $\sim 45 \%$ at a Jg of 1.31 cms^{-1} and then reducing further to just above 30% at a Jg of 1.64 cms^{-1} .

The liquid flowrates for the three mesh designs tested are presented. The lowest liquid flowrates are associated with the square mesh, with the standard mesh having intermediate liquid flowrates and the thin walled mesh having the greatest flowrates. The majority of the liquid flowrate data points are outside the error of each other.

It is important to take the designs of the meshes into account in qualitatively resolving the results. The square and standard mesh both have the same total surface area available, whereas the thin walled mesh sees a significant increase in the total surface area. It would seem logical to conclude therefore that an increase in available area increases the total

flowrate of material through the mesh. The results indicate that this is true, with increased air recoveries and increased flowrates of liquid and solids, but proportionally with more liquid than solids. This results in a wetter froth, which is likely to be not particle-stabilised at a J_g of 1.31 cms^{-1} and 1.64 cms^{-1} . However, they still have a significant solids content, and they are likely to have as significant effect on the behaviour of the froth.

Although the square and standard meshes both have the same open surface area, the square mesh has as a significantly lower air recovery, and associated with this, a lower recovery of solids and liquid to the concentrate. Proportionally however, the ratio of solids to liquid remains similar to the standard design. By inspection of the mesh designs printed, as shown in figure 5.87, it can be seen that around the edge of the mesh, the square design in addition to the rim of the mesh results in a much lower open surface area for particle-stabilised bubbles to transit through.

Therefore, it is difficult to draw conclusions about whether there would be an appreciable difference in the behaviour of the square mesh versus the M3x2 mesh, as their current aperture configuration is not optimised for the transport of froth across them at the edge of the cell. It is however, possible to draw some conclusions about the behaviour of the thin walled mesh. In comparison with the standard mesh, the thin walled mesh allows for higher air recoveries, as well as increased flowrates of solid and liquid to the concentrate. This is through increasing the total surface area available for transfer of particle-stabilised bubbles across the mesh. The increased recovery is beneficial however, as the increased liquid flowrate implies an increase in entrainment of material across the mesh. This is difficult to quantify in a single species system, and could only be determined in a true separation.

B.5 Conclusions

There are performance improvements to be had through further modification of the mesh design. However, there are a considerable number of factors, which influence the transfer of particle-stabilised bubbles across the froth, and so a wide ranging, step by step process is required in order to determine the most optimal design principles for the mesh.

Two modifications of the standard mesh design were tested in this case, one with reduced wall thicknesses (and the edge of the mesh removed) to maximise the effective surface area for the transfer of particle-stabilised bubbles. Secondly, the shape of the aperture was changed from a hexagon to a square, as a square is likely to have a reduced

manufacturing cost due to reduced complexity. The square mesh was shown to have the weakest performance in terms of air recovery and the flowrate of solids and liquid to the concentrate. The standard configuration mesh had intermediate performance, and the thin walled mesh has the highest air recovery and solids flowrates. It is also important to note that the peaks in solids flowrate matched the peaks in air recovery for all designs, once again reinforcing previous conclusions made about the links between PAR and recovery.

Adjusting the shape of the aperture in the mesh in this experiment from a hexagon to a square has resulted in a reduction in performance. The arrangement of the apertures is based on the centre of an aperture at the centre of the impeller plane and the apertures spreading out in a regular tessellation of the shape being tested. This results in different arrangements of shapes at the edge of the mesh as it is circular in shape. In the case of the square mesh, there is a low effective surface area at the edge of the mesh in comparison to the standard mesh. The froths generated by the square and standard meshes are both similar in composition and only really differ in total flowrates.

Increasing the total surface area available for the transfer of particle-stabilised bubbles across the mesh results in significant improvements in air recovery and the flowrate of solids and liquid to the concentrate. The improvement in the flowrate of solids is tempered by the proportionally larger increase in liquid flowrates.

Finally, it is important to note that thinning the wall of the mesh results in high air recoveries and low proportions of solid to liquid by mass in the concentrate. High air recoveries have been noted to have poor correlation to solids and liquid flowrates. The system is chemically optimised under a particular set of conditions, and the design modifications are clearly having an effect to what has proven to be a sensitive set-up. It would be worthwhile to further improve the experimental system so that it behaves as a particle-stabilised froth across a much wider range of conditions, in order to truly determine the effects of the modifications under consideration.

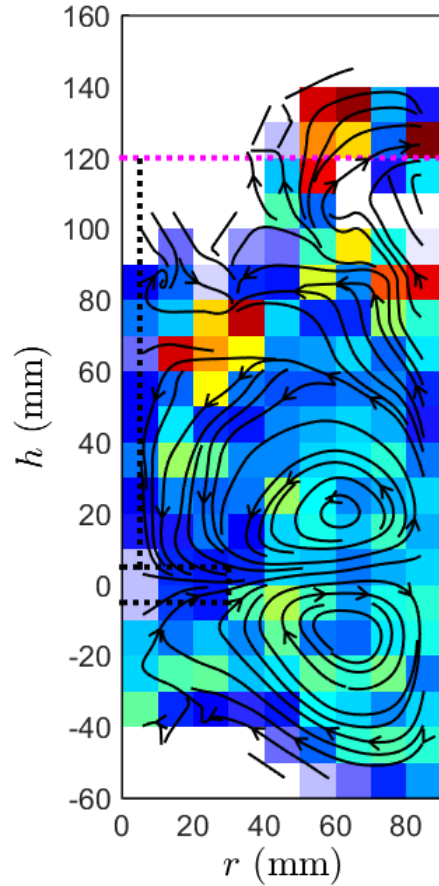
Appendix C

PEPT Tracer occupancy comparisons

C.1 Occupancy comparison tests

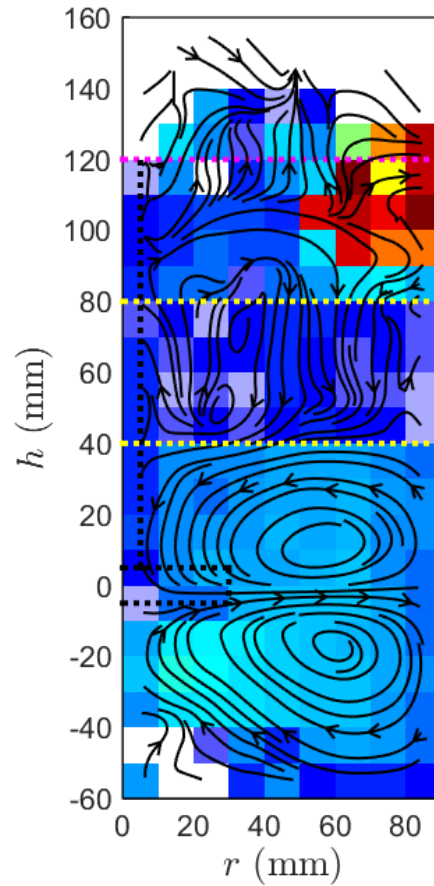
For the PEPT tracer tests, both the hydrophobic and hydrophilic base case datasets experienced data processing errors for occupancy. These tests were run at a Jg of 1.38 cms^{-1} . The PAR tests were run at a Jg of 1.31 cms^{-1} . Although not strictly the same gas velocity, they are close enough for a qualitative comparison of how adding retrofit designs may affect the occupancy of the tracer across the flotation cell. Presented in this Appendix are comparisons of the M1x4, M3x4, M5x4 and M3x2 meshes with the unmodified base case data.

Occupancy of the tracer low in the pulp, relatively low near the interface towards the lip of the cell. It is higher at this level towards the centre and high in the flow near the lip and where it overflows the flotation cell



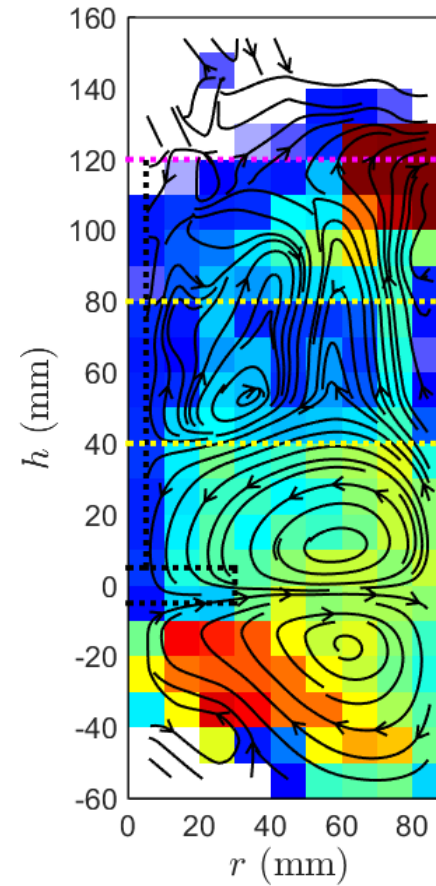
Unmodified system

Occupancy is high in the pulp phase, and very low in the mesh space. High occupancy of the tracer near the lip of the cell in the froth phase



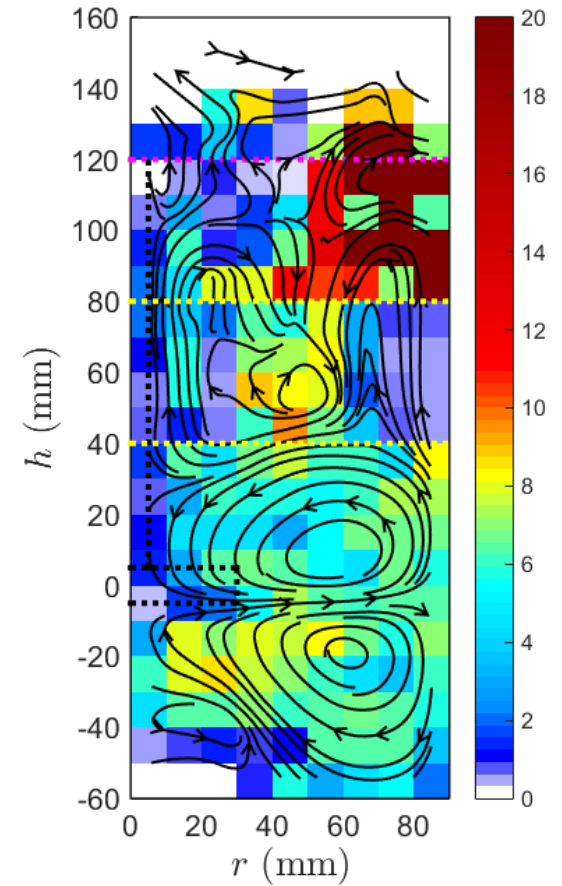
M1x4

High occupancy of the tracer in a very concentrated region close to the lip of the cell in the froth phase. Clear 'path' picked out through the mesh for the tracer by high occupancy results



M3x4

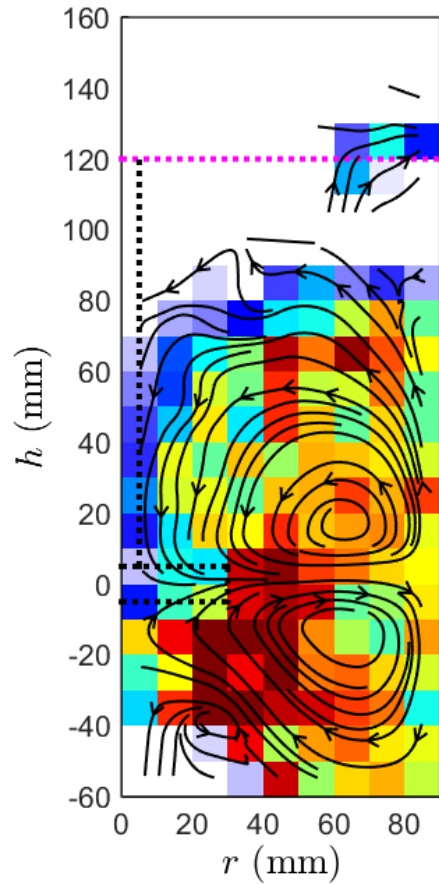
Tracer has very high occupancy in the centre of the mesh and throughout the vertical extent of the froth towards the lip of the cell. Very low occupancy in the mesh centre and edge where transport is up through the mesh



M5x4

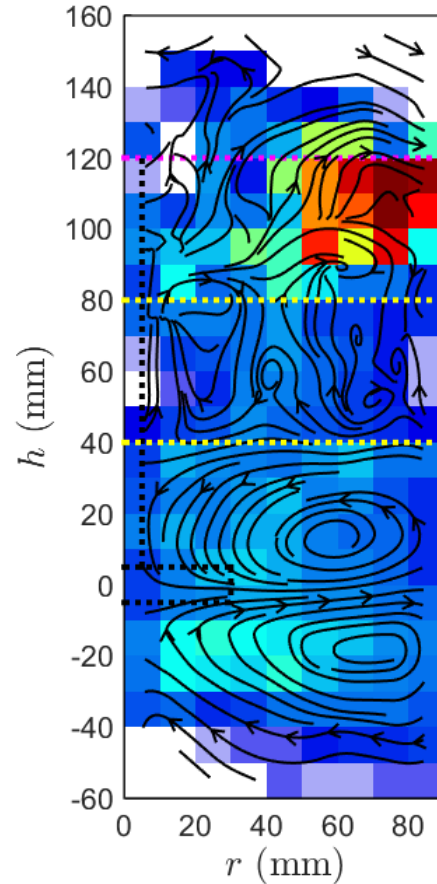
Figure C.1 - Occupancy of the tracer per 10 mm^2 for the hydrophobic system, with the base case (at a lower J_g of 1.31 cms^{-1} compared with 1.38 cms^{-1} for all other configurations) compared to the M1x4, M3x4 and M5x4 meshes in the vertical plane of the flotation cell. Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

Tracer has high occupancy in the pulp phase, particularly below the plane of the impeller. Tracer has low occupancy in the base of the froth and overflows rarely



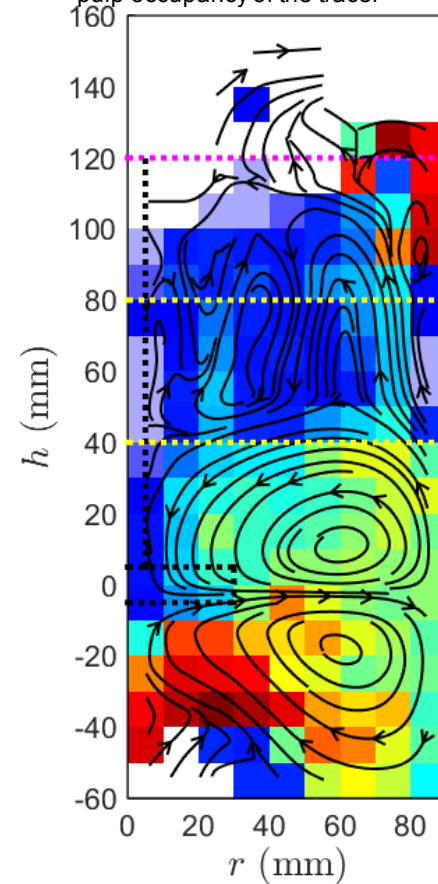
Unmodified system

Very low occupancy in the mesh, high occupancy in the froth close to the lip of the cell. Very similar profile to that of the hydrophobic tracer



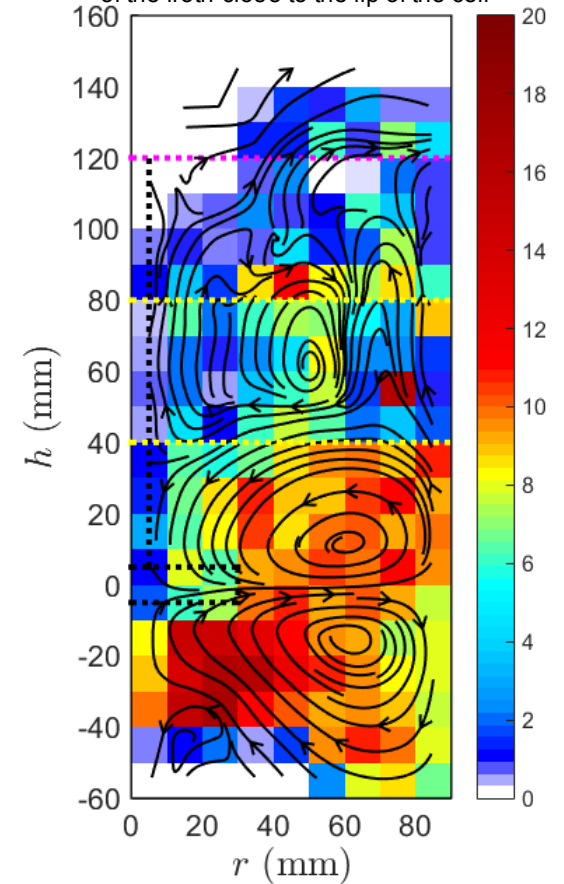
M1x4

Low occupancy of the tracer in the mesh and in the froth. Relative to the hydrophobic tracer, moderately high occupancy of the tracer in the froth close to the lip of the flotation cell. High pulp occupancy of the tracer



M3x4

Very high pulp occupancy of the hydrophilic tracer. Some occupancy in the centre of the mesh and at the base of the froth phase. However, occupancy is low in the upper portions of the froth close to the lip of the cell



M5x4

Figure C.2 - Occupancy of the tracer per 10 mm² for the hydrophilic system, with the base case (at a lower J_g of 1.31 cms⁻¹ compared with 1.38 cms⁻¹ for all other configurations) compared to the M1x4, M3x4 and M5x4 meshes in the vertical plane of the flotation cell. Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

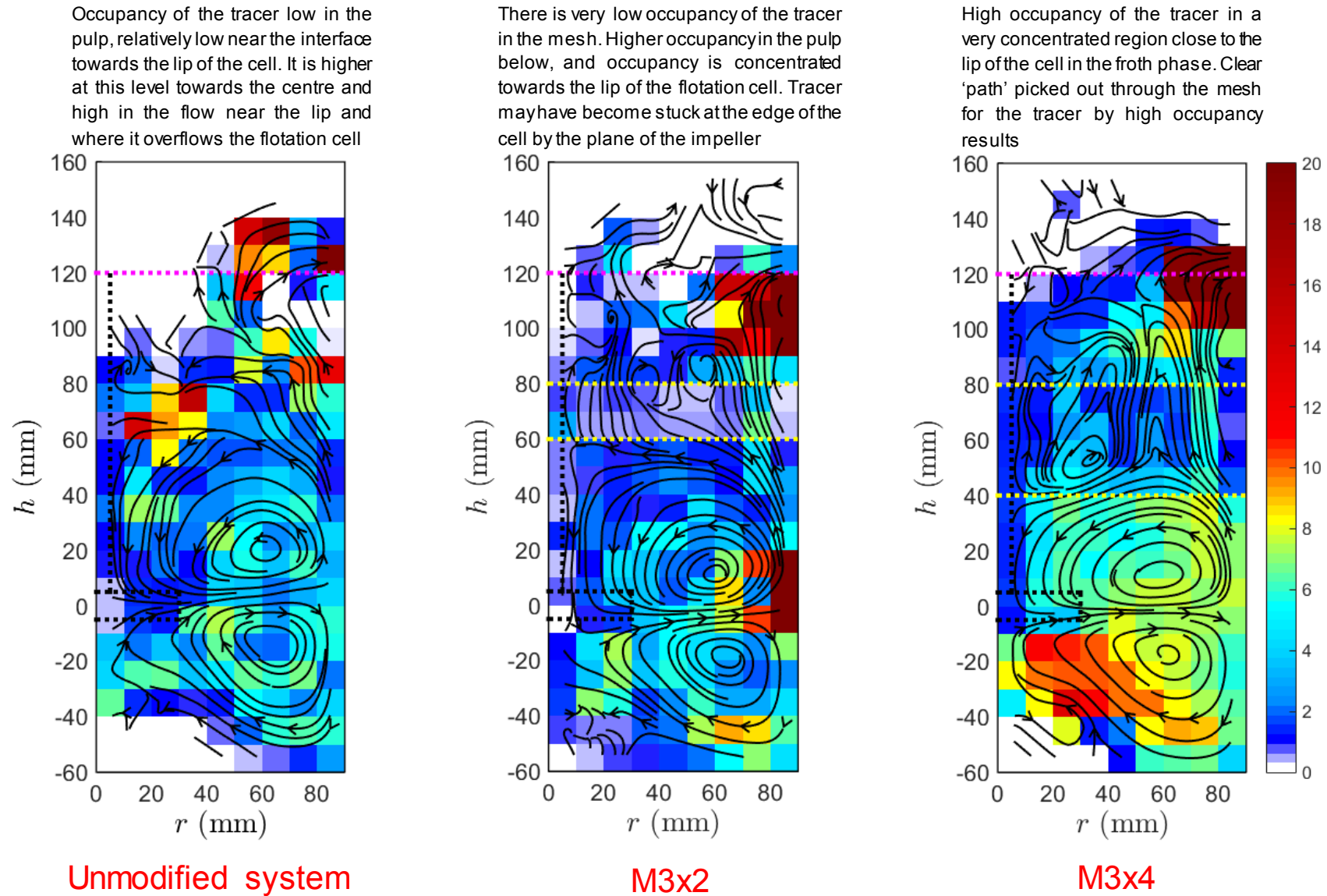
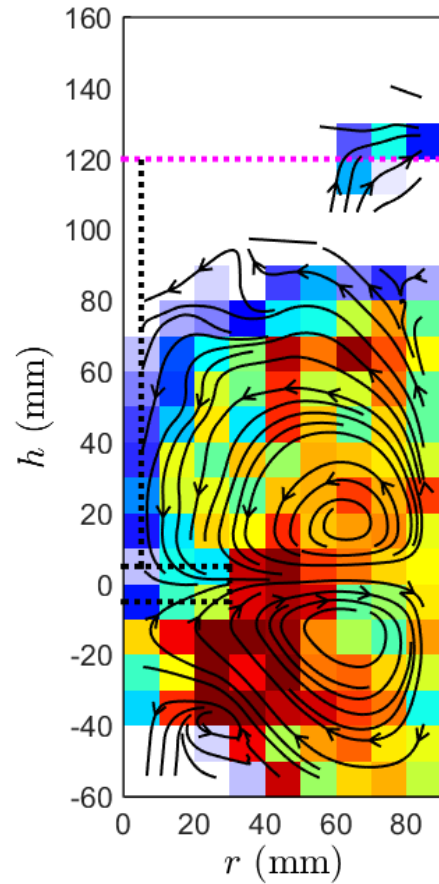


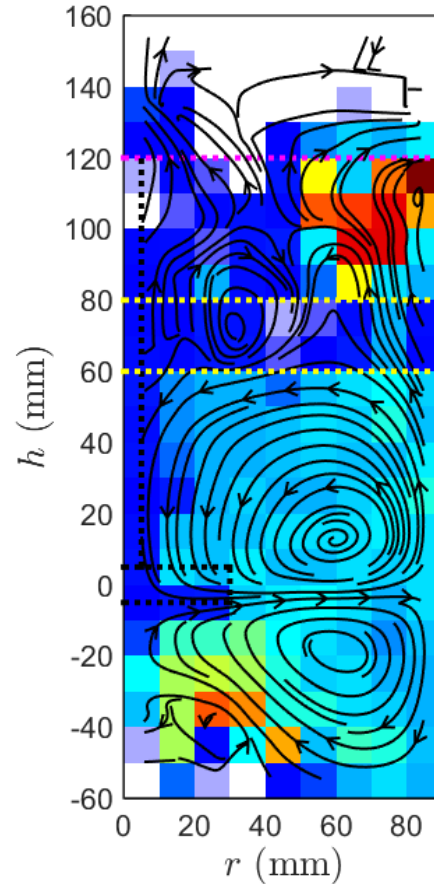
Figure C.3 - Occupancy of the tracer per 10 mm² for the hydrophobic system, with the base case (at a lower J_g of 1.31 cms⁻¹ compared with 1.38 cms⁻¹ for all other configurations) compared to the M3x2 and M3x4 meshes in the vertical plane of the flotation cell. Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.

Tracer has high occupancy in the pulp phase, particularly below the plane of the impeller. Tracer has low occupancy in the base of the froth and overflows rarely



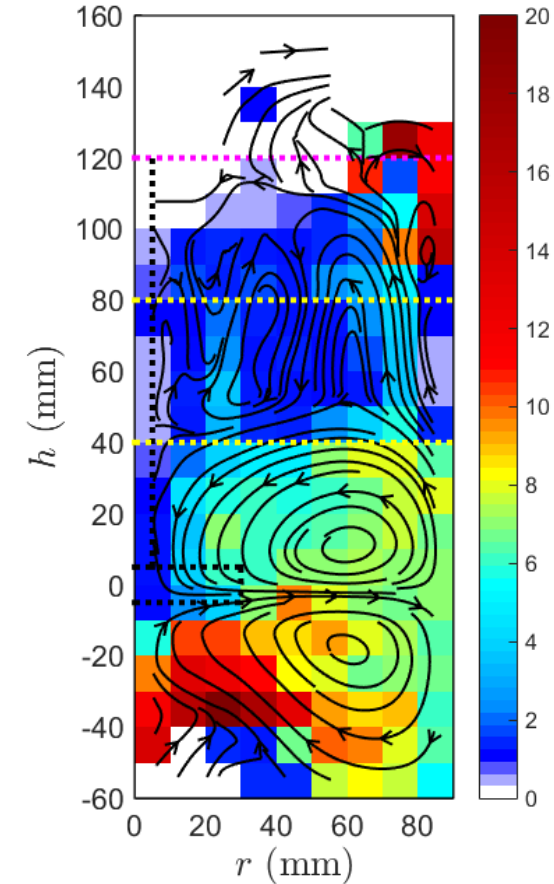
Unmodified system

High occupancy of the tracer below the impeller and more diffuse throughout the pulp phase. Very low occupancy of the tracer in the mesh and high occupancy in the froth near the lip of the flotation cell



M3x2

Low occupancy of the tracer in the mesh and in the froth. Relative to the hydrophobic tracer, moderately high occupancy of the tracer in the froth close to the lip of the flotation cell. High pulp occupancy of the tracer



M3x4

Figure C.4 - Occupancy of the tracer per 10 mm² for the hydrophilic system, with the base case (at a lower J_g of 1.31 cms⁻¹ compared with 1.38 cms⁻¹ for all other configurations) compared to the M3x2 and M3x4 meshes in the vertical plane of the flotation cell. Yellow dashed lines denote the mesh position. Pink dashed lines are the lip of the flotation cell. The pulp-froth interface resides at 80 mm in the y axis.