The Effect of Flotation Cell Shape on Deinking Behaviour

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SUMMARY

Studies were undertaken to investigate the deinking behaviour of different shaped deinking cells of the same volume. For comparative purposes, most oprational variables were kept constant, and the same injector was used throughout the study. The position of the injector, however, was varied in some cases to go along with the particular cell shape being studied.

Three types of cell shapes were studied, (1) cylindrical with tangential air injection, (2) rectanular with vertical injection, and (3) rectangular with horizontal injection. Eucalyptus/toner slurries and news/mag wastepaper slurries were deinked. Flow patterns in the cells and the corresponding deinking efficiencies were measured.

It was found that strong and excessive re-circulatory flows within the cells could under certain conditions be a major factor in reducing brightness lift. Vertical injection into a rectangular cell gave stable flow patterns, non-wavy froth removal and sustained brightness lift for a wide range of feed and airflow rates. Horizontal injection into a similar rectangular shaped cell exhibited quite different characteristics. High brightness lift was possible for certain conditions and not for others. Wavy froth and excessive re-circulation flow patterns varied with feed and airflow. The cylindrical cell with tangential injection gave stable circulatory flow and stable froth removal at low flow rates but was unable to deink at high flows.

INTRODUCTION

Wastepaper deinking is carried out industrially in numerous types of flotation systems which consist essentially of multiple cells and injectors interconnected by pumps and pipes. The cell and injector are the characterising feature of the design and generally they are the same for a particular system. Between different flotation systems, cells and injectors can vary considerably (eg. in size, shape and internal design) and this can give rise to variation in deinking efficiency across single cells and across the flotation system, depending on the number of cells in the system and the configuration used.

Flotation deinking is based on technology borrowed from the mineral processing industry in the 1960's. At a very basic level, the flotation process involves the passing of air bubbles through the wastepaper stock, which is in a liquid/slurry form. Ink particles that attach to the air bubbles rise to the surface of the slurry for removal.

Superficially the flotation deinking process seems very simple. But this can not be further from the truth, as it is an extremely complicated process to analyse and model. Many processes occur simultaneously during flotation where chemical, physical and hydrodynamic aspects are involved.

The aim of this research was to investigate the affect of cell shape on flotation deinking. Presented in this paper are some background theories on the fundamentals of the flotation process and key variables identified and discussed by other researchers. There is also analysis and discussion of experimental results relating to the hydrodynamics of the flotation process.

The research attempts to elucidate the present fundamental knowledge on flotation process variables, such as how injector mixing sections and flow patterns within flotation cells affect deinking performance and efficiency. All experimental trials were conducted in the wood/fibre-processing laboratory at the University of Waikato, Hamilton, New Zealand.

Specifically the following investigations were undertaken:

(a) Development of a novel pulp stock to give improved analysis of deinking efficiency.
(b) Air injector effect on average bubble size, flow patterns and gas phase hold-up.
(c) Effect of air injector, mixing intensity, cell residence times and cell shape on deinking efficiency.

THEORY AND BACKGROUND LITERATURE

Fundamentals of flotation deinking

Flotation is a selective process of separating particles from a slurry involving hydrodynamic, physical and chemical (physico-chemical) aspects (1). The major steps in the flotation process, as applied to wastepaper deinking are: aeration; mixing/collection and separation.

The physico-chemical interactions drive ink collection and aggregation with the air bubble. The hydrodynamic aspect directs ink particle and air bubble collision and ink removal.

The flotation process can be influenced by the variance of physical, chemical and hydrodynamic factors. Physical variables include ink particle size and density, slurry consistency and temperature. Chemical variables include water quality, pH of slurry, and surface tension values governed by flotation chemical agents such as frothers and collectors. Hydrodynamic factors include the flow patterns of air bubbles and the slurry in the flotation cell. All three factors may be manipulated according to end-use requirements, flotation cell design, deinking chemical selection and overall recycle system set-up.

The flotation cell may also be considered as a multi-component system, consisting of water, ink particles, air, fibres and fillers. A selective separation is required with only the ink to be removed. To remove all the ink without any other components is extremely difficult. To aid the selective separation the process may be controlled so that the level of fibre loss is minimised.

Ideally, air bubbles should carry only ink to the surface with fibres left behind. To help achieve this, chemicals are used to aid in bubble formation and ink attachment. The flow of slurry within the cell may also be manipulated to produce a beneficial turbulence. Caution must be used to set the level of turbulence. Too high a turbulence may cause ink detachment from the air bubble, low turbulence may cause insufficient air bubble and ink particle interaction and thus low probability of collision.

Schulze (2) identified the two fundamental problems of flotation deinking as: non-uniform surface properties of ink particles with low weight and small size, and the high density of stock suspension where fibres form a quasi-elastic network. These factors combined with others make flotation deinking a difficult process to analyse and model.

Furthermore, the waste paper slurry must be prepared properly for efficient flotation to be achieved. Efficient ink removal requires the ink particles to be entirely detached from the paper fibre prior to flotation separation. In addition to good defibering, the pulping stage must detach the ink from the fibre using chemicals, temperature and mechanical action.

The slurry should be of uniform consistency with the exact value dependant on cell design. It should be free of large contaminants (particles and debris), which may cause operational problems. Ash may also be required in the slurry to aid flotation chemicals in enhancing ink removal. Of main importance is the air requirement. The size and quantity of air bubbles is critical in the efficiency of ink removal.

Optical properties

The optical properties of recycled paper are significantly affected by the presence of ink and contaminants. Evaluation of the efficiency of ink and contaminant removal can be based on the optical properties of the final product. Image analysis, dirt count, brightness and effective residual ink concentration (ERIC) measurement all provide valuable information in determining the optical properties of recycled paper. These techniques help in monitoring deinking operations, quality evaluation, and development and optimisation of equipment.

The ink particles present in wastepaper vary widely in shape, colour and size. The size distribution of ink in recycled paper also varies having different effects on optical properties. The presence of many small non-visible particles decreases brightness significantly. Whereas the presence of large visible particles affect dirt count and cleanliness. It is important to note that the ink particles detected by dirt count methods do not contribute most to changes in brightness.

Optical properties, such as brightness, differ with ink area. The brightness decreases as ink surface area increases. Walmsley (3, 4) found that brightness was approximately proportional to ink surface area. Also, more light is absorbed by ink at the top of the sheet than within the sheet and hence ink distribution in the sheet is important.

The fibre type also effects paper optical properties. High brightness fibres are affected by residual ink more than low brightness fibres (5). The high brightness fibres transmit light within the sheet to more ink particles and as a result loose more brightness. In the experiments the type of fibre ink used was kept constant.

EXPERIMENTAL

Background

The deinking efficiency of three different flotation cells was examined by looking at the effect on toner ink removal from eucalyptus fibre stock under different operation conditions. Cell 1 was cylindrical with tangential injection and central rejects removal, Cell 2 was rectangular with horizontal injection and horizontal rejects removal, and Cell 3 was rectangular with vertical injection and horizontal rejects removal.

The trials were done using a flow circuit with total re-circulation of rejects and accepts back into the main stock holding tank. Samples were taken at the feed, accept and reject lines of the flotation cells. The different cells were used to survey the effects of the following variables on brightness changes between the feed and accept lines:

(a) Total air volume and airflow rate
(b) Liquid level height above injector
(c) Total cell volume
(d) Liquid flow rate
(e) Air injector arrangement
(f) Cell type and configuration

These variables gave insight into the following aspects and their effects on ink removal and deinking efficiency:

(a) Bubble size and distribution
(b) Mixing intensity
(c) Bubble velocity
(d) Liquid residence times
(e) Cell flow patterns

Flow Circuit

The flow-circuit consisted of a pump, holding tank, flotation cell, a frame for the cell and tank, piping and stirrer. The pump used was a centrifugal, open impellor with a 7.5kW, 3-phase, 50Hz motor. The holding tank had a capacity of 450L and was stirred with 180W AC motor connected to a stainless steel paddle. The circuit was set up such that flotation cells could be readily changed without too much difficulty.

Cell 1 – Cylindrical Perspex

The cylindrical flotation cell with tangential injection and central rejects overflow is shown in Figure 1. The accept pulp exited the bottom of the cell. An adjustable weir controlled the liquid level and rejects flow rate of the cell. The cell was constructed of clear Perspex and had a maximum volume of 13L.

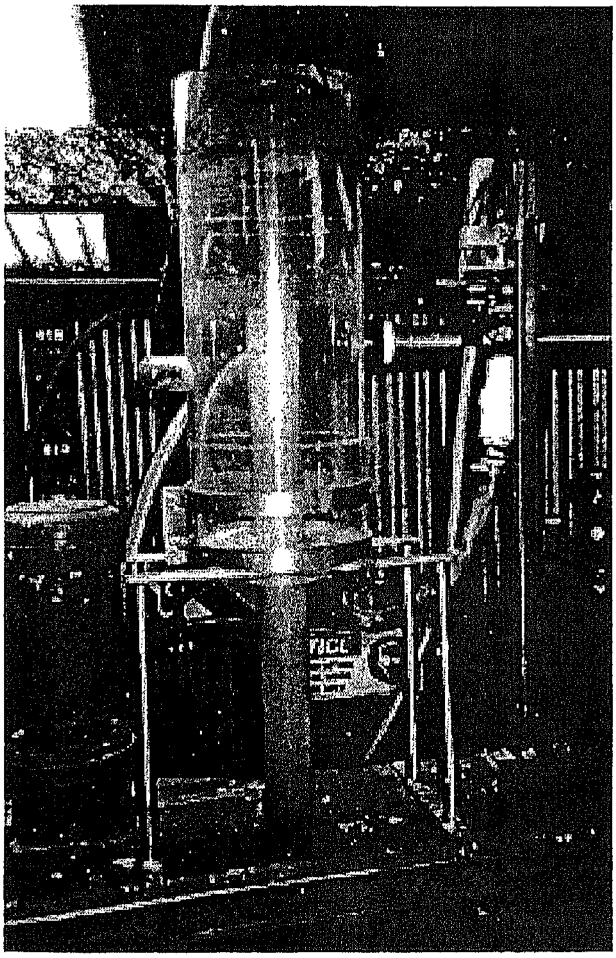

Figure 1: Cylindrical flotation cell

Cell 2 and 3 – Rectangular Perspex

The rectangular flotation cell was used for cell types 2 and 3. This was achieved by altering the orientation of pulp injection. Figure 2 shows the set-up for cell 2 (horizontal injection). Cell 3 differs in that the pulp enters vertically through the top of the cell.

The flotation cell was constructed of Perspex with threaded fittings at injector (middle left), accept underflow points (bottom left and right) and reject overflow (top right). The width of the cell was 160mm and it had an approximate volume of 12L.

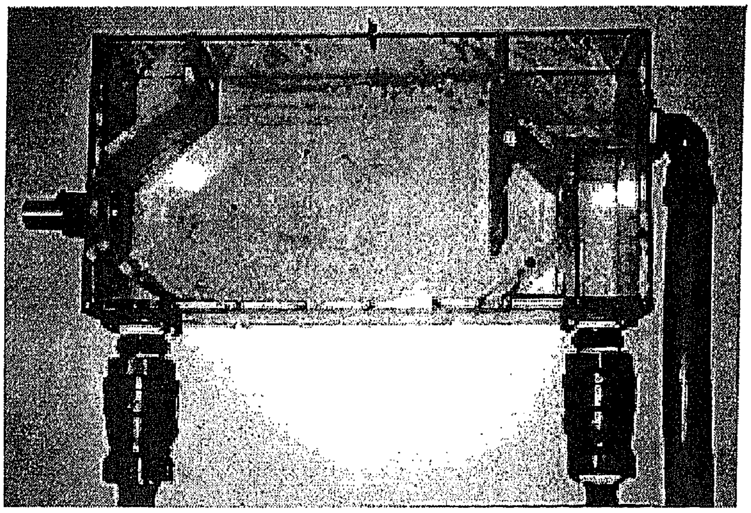

Figure 2: Rectangular flotation cell

Injector

The injector used for aeration was machined from 30mm stainless steel rod. A sectional view of the injector is shown below in Figure 3.

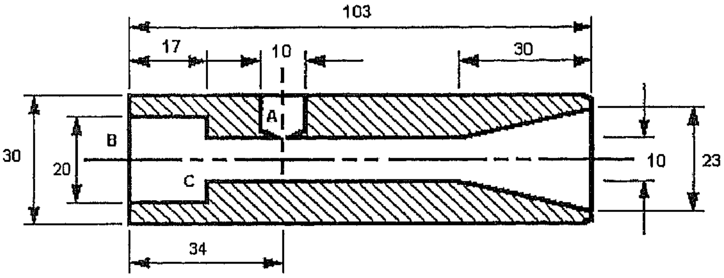

Figure 3: Cross-sectional view of air injector

Liquid flow was from left to right in Figure 3. Air injection was at A. The airflow rate was controlled by a rotameter. Different sized orifices were fixed at C. Orifice plates were 20mm diameter stainless steel discs with 3mm, 3.5mm, 4mm or 5mm holes at the center.

The level of liquid turbulence in the injector was determined using the water equivalent orifice Reynolds Number:

$$\mathrm{Re} = \frac{4Q\rho}{\pi\mu D}$$

where Q is the liquid flow rate, ρ liquid density, μ is water viscosity and D is the orifice diameter.

Experimental Procedures

To investigate the affect of cell shape on flotation deinking, standard experimental methods were developed. A British Hand-sheet machine was used to form the hand-sheets for brightness determination. 3g oven dry hand-sheets were used. Hand-sheet brightness was measured by determining the reflectance of light at a wavelength of 457nm. For image analysis 5g/m^2 pads formed on filter paper were used.

Experiments were conducted using 2 different furnishes; bleached eucalypt kraft pulp and toner ink, and 70/30 news/mags wastepaper. For flotation, the pulped stock was diluted to 0.6% consistency. The toner was from photocopy cartridges. The eucalyptus pulp was from beached kraft eucalypt lap sheets. The surfactant used was Olinor 4020, a fatty acid type that required the addition of calcium in the form of calcium chloride. The pulping was done in a Lamort batch pulper at approximately 8% consistency.

DEINKING BEHAVIOUR IN VARIOUS CELLS

Cylindrical Perspex cell

The cylindrical Perspex cell was used to examine the effects of airflow rate and liquid level height above the injector on the brightness change between the feed and accepts to the flotation cell. The slurry was at 40°C, 0.6% consistency with a constant reject flow rate of 0.6L/min and toner concentration of 2%. The reject flow rate Rv expressed as a percentage of the feed flow rate was held constant at 11%.

From Figure 4 the lower liquid level height of 60mm gave a lower brightness change than the higher heights of 160mm and 270mm for the same reject rate. The brightness changes at 160mm and 270mm displayed similar trends. From this, it appeared that an increase in height above 160mm may not give any significant increase in brightness change. This could have been due to equilibrium between the increasing probability of ink/bubble collision and attachment due to increasing rise distance and the probability of ink/bubble detachment due to increasing distance of travel through the fibre network. It may be assumed that the marginal gains in brightness lift due to increasing the level height could be insignificant when compared to the increased capital costs of larger flotation cells. Further investigations were required to validate this.

The results displayed in Figure 4 follow vague bell shape curves, in that at the higher airflow rates the brightness lift seems to decrease. This observation was confirmed by Dorris (6) who attributed a decreasing flotation rate to increasing bubble coalescence at high aeration rates. Bubble size can increase with increasing airflow rate due to insufficient mixing of the larger volume of total air. But, for the cylindrical cell, the bubble size did not increase but decreased to form a larger number of smaller sized air bubbles. This was due to the increase in turbulence as the airflow increased, giving more mixing energy to disperse the air. This phenomenon was further examined in later trials.

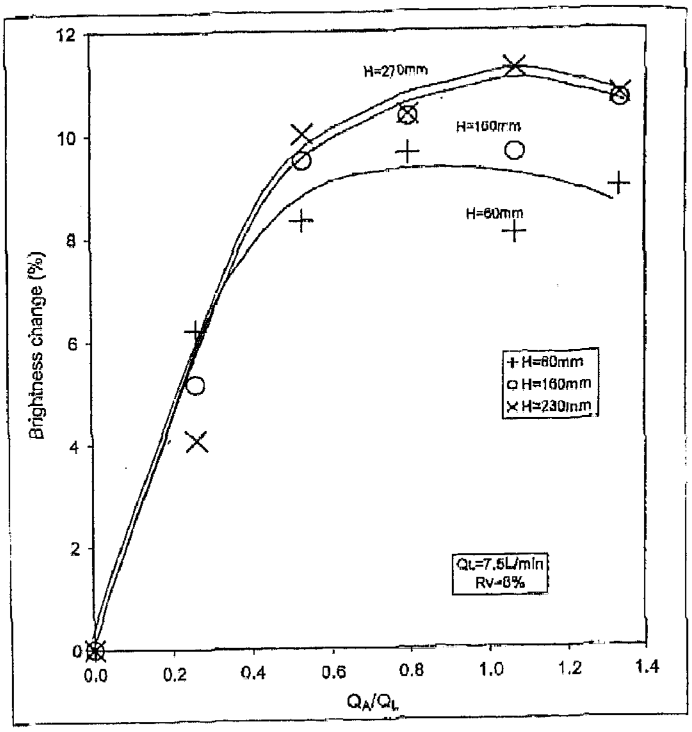

Figure 4: Effect of air flow rate on brightness change in cylindrical cell for various liquid level heights above injector for eucalyptus pulp and toner slurry at 0.6% consistency, orifice 3mm.

Rectangular cell with horizontal injection

The effect of cell type was next examined. Cell 2, the rectangular perspex cell with horizontal injection and far accept underflow was used to assess the effect of airflow rate on brightness change. The same stock type was used as that for previous trials. A 3mm orifice with low and high Reynolds numbers (low and high liquid flow) was used as this was found to give optimal results for the cylindrical cell.

From Figure 5 the results had similar form to those for the cylindrical cell in that the brightness lift increased initially as air flow rate increased up to a maximum and then decreased at high airflow rates. The main difference was the drop in brightness over the 1.0-1.5 air ratio region. On observation the cell flow patterns over this airflow region were different, in that prominent waves formed at the top of the cell. This caused an uneven and non-uniform reject flow rate and remixing of foam back into the bulk slurry. This may help explain the decrease in brightness change at medium airflow rates.

The waves that formed at the top of the cell over medium range airflow rates affect reject ink foam removal in that the resulting motion of flow causes fluctuating surges of exiting slurry. This prevents ink from being removed in a constant manner resulting in a build up of ink foam at the surface of the cell. The ink may be pulled back into the slurry by recirculating flows which are usually always present but would have a more significant effect on the build up of unsteady rejects that are not being steadily removed.

The waves affect flow patterns in the cell to promote ink loss back into slurry. This may result in immediate ink/bubble detachment or the entire aggregate being pulled back into suspension. It may then become detached or eventually make the torturous path through the cell and hopefully back to the surface. The effects of flow patterns are examined later in this section.

The brightness decrease over the medium airflow range was less significant for the low liquid flow, where the wave formation was less predominant than for the higher liquid flow. The lower flow rate induces smaller sized waves at the cell surface that gave less fluctuation, thus a more steady reject foam removal than the higher liquid flow.

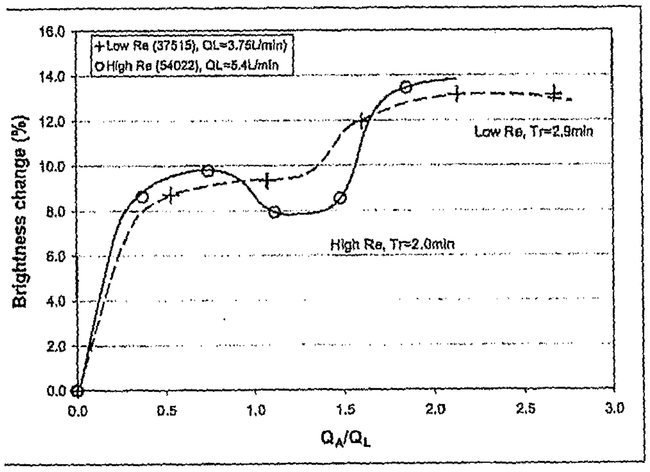

Figure 5: Effect of airflow rate and Reynolds number on brightness change in cell 2 (rectangular perspex with horizontal injection) with 3mm orifice diameter and 11% volumetric rejects.

Rectangular cell with vertical injection

Cell type 3 was next examined. Cell 3, the rectangular Perspex cell with vertical injection and far accept underflow was used to assess the effect of airflow rate on brightness change. The same stock type was used as that for previous trials. The 3mm orifice with low and high Reynolds numbers was used as these variables had been used for cells 1 and 2. This allowed comparison of results between the different cell types. Figure 6 shows the effects of air flow rate on brightness change for cell 3.

Once again the curves had similar form (bell shape) to that of previous results for the other cell types. The results for flow at low Reynolds number achieved a high brightness change at low air flow with a substantial loss of brightness at higher air flow rates. The results for high Reynolds number gave a steady increase in brightness change as the air flow was increased. As discussed previously for cells 1 and 2, this should also decrease if the air flow rate was further increased.

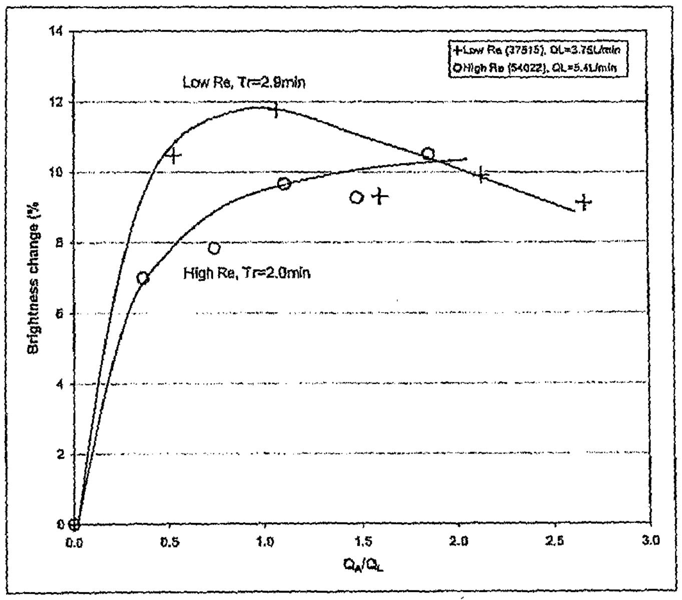

Figure 6: Effect of airflow rate and Reynolds number on brightness change in cell 3 (rectangular perspex cell with vertical injection) with 3mm orifice diameter and 11% volume rejects.

On observation, the low Reynolds number flow in cell 3 produced noticeably larger air bubbles at higher air flow rates when compared to cells 1 and 2. The bubbles were also larger than those produced in the same cell for the higher Reynolds number. This could be due to the orientation of pulp and air injection and its effect on bubble formation and coalescence.

A possible explaination is that the air injected at low Reynolds number had less overall turbulence during bubble formation than for the higher Reynolds number. Thus larger bubbles were formed due to the decrease in available mixing energy. Also a high degree of bubble coalescence may have been occurring, as the bubbles had to travel a relatively long distance down the injection tube. Not only did the bubbles have to travel down the length of the injection tube but change direction and move up towards the surface of the cell as indicated by the arrows in Figure 7.

At low air flow rates the mixing energy provided by the turbulence was sufficient to give a range of small bubbles to give good ink removal, thus high brightness lift for the low Reynolds number. As the airflow was increased the brightness change decreased, as the bubble size became larger. This was due to the turbulence providing insufficient mixing energy to adequately disperse the larger volume of air at high airflow rates. The air also had to contend with the long journey to the surface of the cell that promoted bubble coalescence.

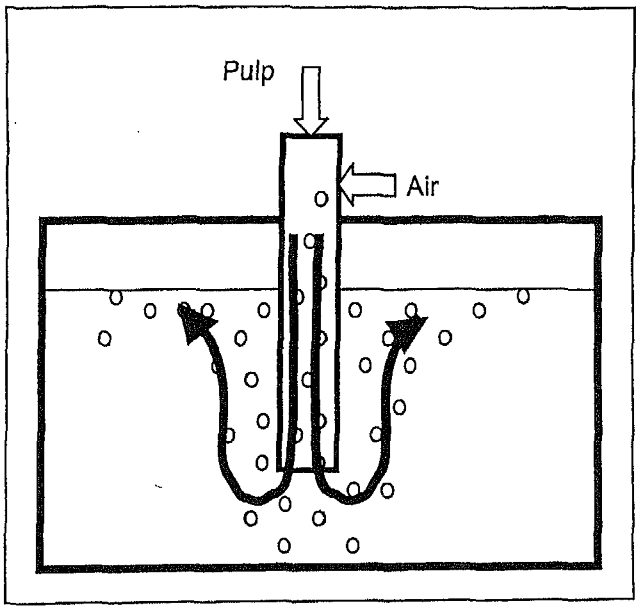

Figure 7: Schematic of pulp and air injection into cell 3.

Flow patterns

The effect of cell flow patterns on deinking efficiency was also an areas of investigation. This was done by recording the flow patterns and the effects of air flow rate on brightness change for the three different cell types. All factors were kept as constant as possible between the different cell types ie, same Reynolds number at orifice, same residence times etc to better isolate the effects of flow patterns and cell type on deinking. Figures 8 and 9 show the results of these trials.

As discussed earlier, the flow patterns in the cell govern the hydrodynamic aspects of ink particle and air bubble collision and ink removal. The cell flow patterns have a direct effect on these and the different cell types examined here affected them in varying degrees. It was difficult to make accurate visual observations of flow within the cell due to the opacity of the pulp. Thus observations were limited to regions near the perspex cell walls.

It was particularly difficult to observe the liquid flow patterns within cell 1 (cylindrical perspex with tangential injection). From the observations made though, the feed stock that entered the cell followed an upward spiraling path to the liquid surface as shown in Figure 10. The air bubbles on the other hand would follow a less obvious spiral, and move more directly to the surface. It seemed that the liquid flow, once reached the surface, would move towards the center of the cell and spiral down to the accept pulp exit.

This type of flow pattern gave the bubbles good interaction with ink due to the spiraling nature of the pulp. The probability of ink particle and air bubble collision was high, as the liquid level height above the injector was 230mm, giving more spirals than if the liquid level was lower.

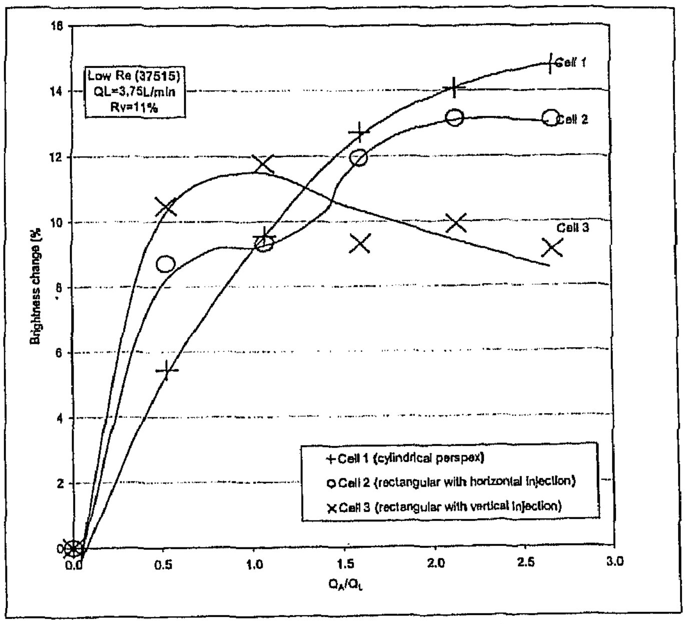

Figure 8: The effect of airflow rate on brightness change for cells 1, 2 and 3 with 3mm orifice diameter and low Reynolds number (37515).

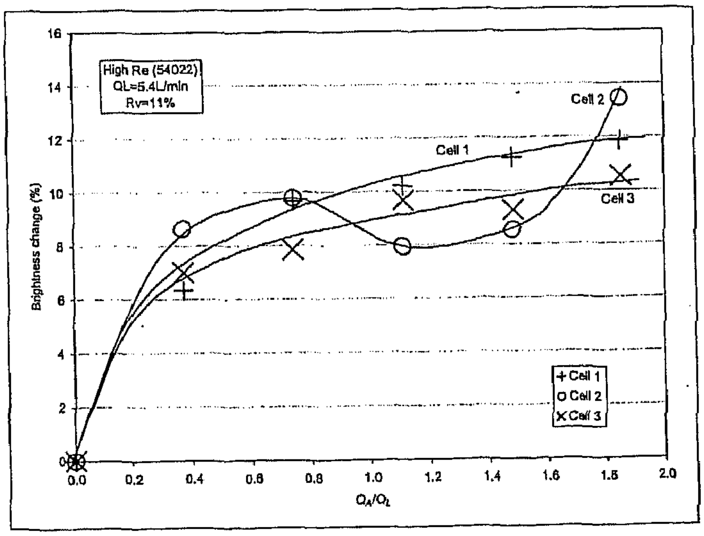

Figure 9: The effect of airflow rate on brightness change for cells 1, 2 and 3 with 3mm orifice diameter and high Reynolds number (54022).

The results in Figures 8 and 9 show steady increases in brightness lift as the airflow rate was increased. The effect of increasing air flow on air bubble distribution and size has already been discussed and its influence on the brightness change. Here the flow patterns were considered, and significant changes were observed as the air flow rate was increased.

The increased air flow caused the pulp to move at higher speeds. The fast motion of the incoming air pushed the pulp away from the injector region. This caused a high degree of turbulence near the injector region. The movement of the spiraling upward flow increased considerably. As the results indicate the brightness change increased accordingly. This may have been due to an increase in ink and bubble interaction as the pulp was moving faster giving more chance for collision with the greater number of air bubbles being introduced.

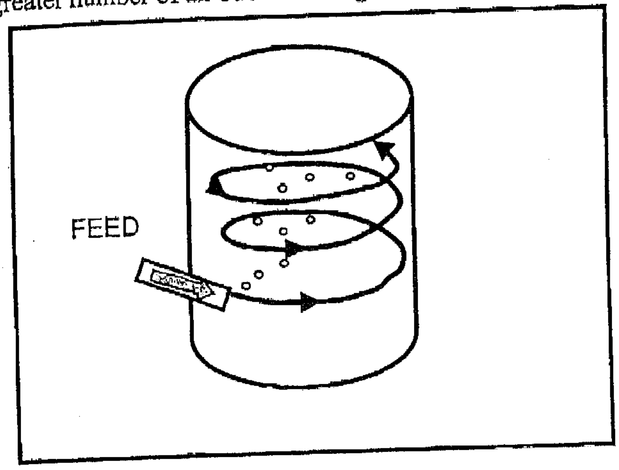

Figure 10: Schematic representation of cell 1 (cylindrical perspex with tangential injection).

Also the bubbles appeared to rise in distinct regions. This is termed channeling, where gas bubbles in a liquid phase rise in preferred regions. Channeling occurs at either high pulp consistencies or high airflow rates (7). As these trials used a relatively low consistency of 0.6%, the channeling must have been due to the high airflow rates. The high airflow rates in cell 1 increased the speed of slurry flow not only in the spiraling motion, but also in the upward direction of the bubble rise. The channeling effect caused the pulp near the rising swarm of bubbles to be caught up in the upward fast moving flow.

The pulp was found to inhibit the distribution of air across the cross-section of the cell, which caused the bubbles to rise in certain regions. The flocculation of the pulp, even at low consistencies can trap small sized air bubbles (8). Also the pulp caused bubble coalescence which gave increased rise times and subsequently decreased gas hold up.

Figure 8 shows the results for low Reynolds number flow, which has higher brightness lift for the same air flow rates than the high Reynolds number flow results in Figure 9. As already discussed this difference may have been due to the higher Reynolds number providing too much turbulence and causing a detrimental effect on ink and bubble interaction.

The flow patterns may help further explain this. At high Reynolds number (high liquid flow) and high airflow rates the spiraling effect was so great that a relatively large vortex was formed at the cell liquid surface. The reject foam was held at the outer surface of the vortex, inhibiting its exit down the central reject pipe. The vortex was less obvious at lower airflow rates and in the lower Reynolds number flow.

The poor reject removal can account for the lower brightness lift achieved at the higher Reynolds flow. The hold up of reject foam may have allowed the ink to be lost back into the cell, decreasing the deinking efficiency. Also the re-circulating pulp flow became stronger at high airflow and Reynolds number, increasing the probability of ink particle and air bubble detachment.

The flow patterns for cell 2 (rectangular Perspex with horizontal injection, Figure 11) has been partially covered earlier in this section. It was discussed that the loss of brightness over the middle range airflow rates was due to unsteady reject removal. This was due to the formation of waves at the cells liquid surface. As with the cylindrical cell, an increase in airflow increased the liquid speed and general movement in the cell. This was further increased with higher Reynolds number flow.

As the airflow was increased the formation of small eddies or re-circulatory flow developed outside and within the major flow patterns featured in Figure 11. It was easier to observe the flow patterns in cell 2 than in cell 1. Cell 2 appeared to have a great deal more extra re-circulation of pulp. This strong re-circulating motion, particular near the surface may have been detrimental to deinking efficiency. The re-circulation may entrain the ink reject foam back into the pulp suspension and also cause 'clean' pulp to mix with 'dirty' pulp.

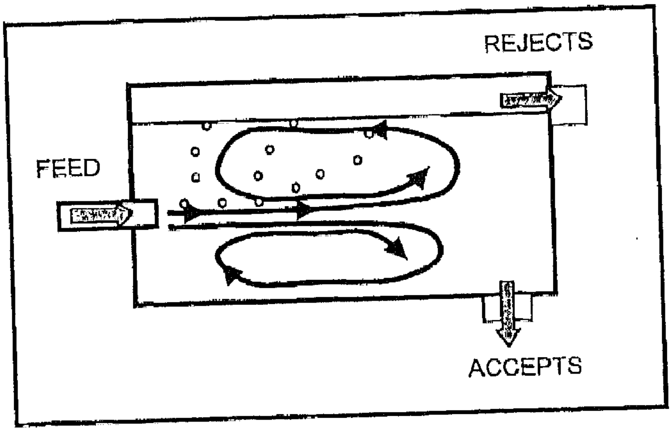

Figure 11: Schematic representation of cell 2 (rectangular perspex with horizontal injection).

A combination of air flow rate and cell geometry causes the re-circulatory flow. Recirculation may be beneficial as it provides higher contact time of pulp and air bubbles. Unfortunately with cell 2, over the medium air flow regions waves formed which prevented the efficient removal of reject foam. The ink had the potential to be removed but was entrained back into the slurry. This was also evident in cell 1 where at high airflow rates a swirling vortex formed at the cell liquid surface also inhibiting efficient ink removal. Multiple reject outlets in same cell appears to have merit.

The flow patterns for cell 3 (rectangular Perspex with vertical injection) are shown in Figure 12, which were very different from those observed for cell 1 and 2. Good air distribution through the cell was evident at all airflow rates. This is shown in Figure 12 where the large recirculation swirls (left and right of feed pipe) gave good contact time and high probability of collision of ink particles and air bubbles.

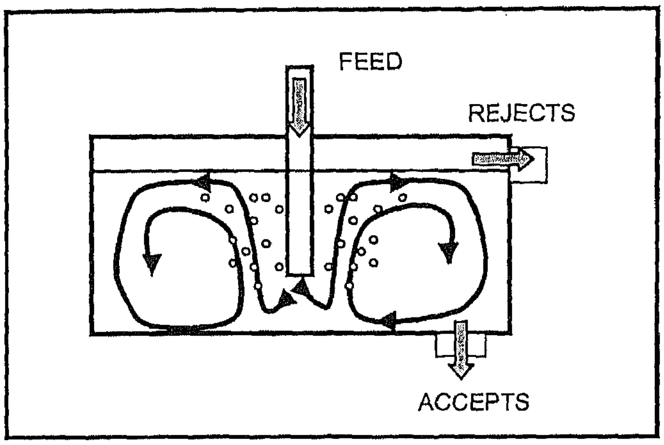

Figure 12: Schematic representation of cell 3 (rectangular perspex with vertical injection).

Ink removal was somewhat inefficient, but for different reasons than for cells 1 and 2. For cell 3 the increased airflow rate did not have a noticeable effect on cell flow patterns and in particular reject flow. On the other hand, the reject foam was effected by circulation of pulp.

The recirculation swirls left and right in the cell caused the liquid at the surface to move towards the outer of the cell. On the left side, the reject foam was pushed into the cell wall. Unable to escape, the ink foam built up. This increased the probability for ink to be recaptured by the recirculating slurry. A reject exit at the left of the cell would be beneficial. On the right side, reject foam was pushed out of the cell by the recirculating pulp flow. Some ink may have been entrained back into the system. This level of entrainment would be much less than that occurring on the left side as the ink was being continuously removed.

It was observed that the larger bubbles could easily escape the fibre network and move quickly to the cell surface. Conversely, small bubbles became caught at the center of the large recirculation swirls. This may have been significant in decreasing the deinking efficiency. More work is needed to quantify this effect.

CONCLUSIONS

The following conclusions can be made from this work:

(a) Cell shape, air/liquid ratio, injector turbulence level and the positions of the injector and rejects and accepts outlets all have a significant interactive affect on deinking performance.

(b) Increasing the air/liquid ratio to a single cell, all other things being equal, generally improves deinking but the level of maximum deinking and when it occurs varies with cell shape and injector turbulence level. The rectangular horizontal injection cell is an acception. Deinking both decreases and increases as air/liquid ratio increases due to waves at the foam surface.

(c) Producing smaller bubbles through higher turbulence in the injector does not always lead to improved deinking. There are conditions where higher turbulence, which leads to smaller bubbles, causes a decrease in deinking perfromance. Hence, the bubble size which maximises ink removal is unique for each type of cell and for the flotation conditions used.

(d) Bubble travel distance to the surface of the cell is important. An optimum cell height exists, but further increases can be detrimental to deinking efficiency. If the distance is too high the probability of ink particle and bubble detachment increases, whereas too lower distance causes a decrease in ink/bubble contact time.

(e) Flow patterns in the cell are strongly affected by cell geometry and air and liquid flow rate. Strong, fast-moving flow patterns and recirculating flow can decrease ink removal. The foam reject removal efficiency is dramatically affected by cell flow patterns and re-circulatory flow.

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