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Aerosol collector addition in flotation – evaluation of delivery options

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Abstract: In conventional flotation systems, the collector is adsorbed onto mineral particles from the aqueous phase at the solid/liquid interface. Aerosol collector addition is a concept whereby collector molecules are introduced to mineral surfaces via the surfaces of bubbles or the solid/gas interface. Several studies have demonstrated this concept, ranging from the analysis of ideal mineral surfaces to laboratory-scale flotation of complex water systems. However, the physical addition of a collector to the surfaces of bubbles is not a common process and has no uniform methodology. If aerosol collector addition is to be studied as a viable reagent addition technique, it becomes necessary to develop and test appropriate methods that could be replicated across several different studies.

This work examines two aerosol addition methods: a conventional Venturi-style gas liquid nozzle, as well as a purpose-built atomiser developed for use in pharmacological applications. Both were compared to a standard "upfront conditioning" batch dosage method and were found to be safe, simple to use and produced comparable flotation outcomes.

Keywords: aerosol collector, flotation, reagent addition

1. Introduction

The advent of man-made climate change has resulted in a significant focus on decarbonisation, with the majority of the world's countries adopting a policy of reaching zero emissions by 2050. However, reaching such a goal requires completely rebuilding our energy infrastructure, to enable the fabrication of wind turbines, solar panels and electric vehicles. The manufacturers of these technologies require significant quantities of metals such as copper, lithium and cobalt, which have now been designated as "critical metals". It has been estimated that approximately 53 million tons of copper need to be mined to meet renewable energy demand, which is likely to produce as much as 858 billion tons of tailings (Valenta et al., 2023). The production of metal at such an increasingly large scale means that mining and mineral processing technologies need to be made more efficient and more sustainable to reduce their environmental footprint.

Froth flotation is a key primary step in mineral beneficiation. Over the last decade, significant advances in flotation equipment design have been made that specifically aim to improve process efficiency. These developments include the Concorde flotation cell (Jameson, 2010), the Reflux Flotation Cell (Chen et al., 2022), as well as the Eriez HydroFloat® (Kohmuench et al., 2018). However, no similar advances have been made in the field of flotation chemistry.

One area that has been identified to have significant potential in increasing flotation process efficiency is that of aerosol collector dosage. A detailed review of aerosol collector addition in flotation has been published previously and only a very brief overview will be presented here (Brill et al., 2022).

In conventional flotation systems, the collector is adsorbed onto mineral particles from the aqueous phase at the solid/liquid interface. Aerosol collector addition is a concept whereby collector molecules are introduced to mineral surfaces via the surfaces of bubbles or the solid/gas interface. The detailed analysis of flotation thermodynamics has demonstrated that the addition of a collector on bubble surfaces carries advantages for improved collector absorption and enhanced mineral surface

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hydrophobicity (Laskowski, 2007). Several studies have demonstrated this concept, ranging from the analysis of ideal mineral surfaces to laboratory-scale flotation of complex water systems (Klassen and Makrousov, 1963, Schreithofer and Laskowski, 2007, Burdukova and Laskowski, 2009, Patil and Laskowski, 2007, Nott and Manlapig, 1994). Although the number of studies is highly limited, in all cases, the use of aerosol flotation has resulted in an improvement in mineral surface properties as well as flotation recovery. This renders aerosol collector addition a very simple yet highly promising technique that could aid in improving flotation efficiency.

The physical addition of a collector to the surfaces of bubbles is not a common process and has no uniform methodology. Only three studies have been published where aerosol collectors were dosed directly into a flotation cell. Misra and Anazia (1987) aerosolised oil droplets using an atomiser manufactured by Perkin-Elmer, which was attached to a flotation cell. The study by Nott and Manlapig (1994) made use of an "air-liquid atomizer" incorporated within the flotation cell impeller, with very few details provided regarding the design of this device. Patil and Laskowski (2007) made use of a custom-built "effervescent atomiser", where compressed air and water were fed through a sintered cylinder and forced out through an orifice plate. In all cases, the methodology descriptions were very low on detail, to the point where the studies would be very difficult to replicate. In addition, no information was provided regarding the effectiveness of the atomisation process, regarding factors such as effective dosage rates and droplet sizes.

The use of gas-liquid nozzles and minerals processing is not new, with one of the most classic examples being the downcomer of a Jameson cell (Harbort et al., 2003). Several flotation applications make use of such devices to provide enhanced air dispersion (Han et al., 2022, Witt, 2022, Jameson, 2010). However, the scale and the application of such devices fall largely outside of the range of usability for collector dosage. Outside of the mining industry, the use of nebulizers and atomisers is relatively common, with several commercial atomisers available for use in fuel injection, food, biological and pharmacological applications. It is therefore important to take the lessons outside of the confines of the mineral processing literature to look for potential solutions.

2. Aims and objectives

If aerosol collector addition is to be studied as a viable reagent addition technique, it becomes necessary to develop and test appropriate methods that could be replicated across several different studies. This will provide increased confidence in the results obtained using such devices but will also allow for method replication and fair comparisons between different tests.

Therefore, this work aims to develop and examine two different methods for aerosol collector addition. The efficacy of these methods will be evaluated and judged based on the following criteria:

- Safe use of the technique, particularly with regard to the potential of introducing aerosolised flotation collectors into the breathable atmosphere.
- The ability to conduct a viable flotation test with results comparable to that of conventional collector addition methods.
- Ease-of-use and adaptability to a laboratory flotation system with the outlook of installation at full scale.

Two specific methods will be examined in this study: a conventional Venturi-style gas liquid nozzle, as well as a purpose-built atomiser developed for use in pharmacological applications. Both will be compared to a standard "upfront conditioning" batch dosage method.

It is important to note that the work presented here does not aim to demonstrate the relative benefits of the two tested methods or to optimise them. The purpose of the research is to demonstrate the viability of the novel collector addition methods that would serve as a basis for future work that will include an extensive test campaign to evaluate and optimise collector addition methods.

3. Materials and methods

3.1. Reagents

The analytical grade methyl isobutyl carbinol (MIBC) frother (Sigma Aldrich) was obtained from Rowe Scientific. Industrial grade sodium isobutyl xanthate (SIBX) collector was obtained from the Cytec-

Solvay group (Aero 317 Xanthate). Safety testing was performed using a FT32 Bitrex solution, obtained from the Qualitative Fit Test (QLFT) test kit, obtained from 3M.

The metal salts used to make process water were analytical grades of KCl (Rowe Scientific), $CaCl_2$ (Sigma Aldrich), $MgSO_4$ (Sigma Aldrich), Na_2SO_4 (Sigma Aldrich), and Na_2CO_3 (Rowe Scientific). During the experimental campaign, 100L of process water was prepared and stored in a sealed drum in a flotation laboratory at room temperature (circa 24^oC).

The process water used in this work was modelled on the process water chemistry at Mount Isa Mines and is assumed to be representative of process water in similar Queensland operations. The analytical grades of KCl, $CaCl_2$, $MgSO_4$, Na_2SO_4, and Na_2CO_3 were used in required amounts to make up process water. The analysis of this process water is given in Table 1 below.

Table 1. Composition of the process water

Elements of interest	Concentration, mg/l
Sulfate as SO_4 - Turbidimetric	2170
Calcium	404
Magnesium	354
Sodium	458
Potassium	130

3.2. Ore sample

The ore sample used in this work was sourced from Aeris Resources and was a blend of the Tritton and Murrawombie deposits. The main valuable phase of the ore is chalcopyrite which was associated with pyrite and sphalerite. The ore head grade was 1.18% Cu, 11.5% Fe, 8.7% S and 0.225 %Zn.

The ore sample was blended and split into representative 975 ± 25g aliquots. Each aliquot was milled at 60% solids in process water, in a stainless-steel rod mill immediately prior to flotation, to a P80 of 130μm.

3.3. Flotation test procedure

The flotation tests were performed in a 3L bottom-driven Denver-style flotation cell. In each test, a freshly milled sample was added to the cell and topped up with process water to make up a pulp containing 26.7% solids.

In the case where the collector was added up-front in a conventional manner, the cell was conditioned for 4 min at 1000 rpm. The agitator speed was set at 810 rpm. The aeration rate was kept constant at 4.5 L/min. The froth depth was kept constant at 10mm below the cell lip. Three concentrates were collected at 1, 4 and 15 minutes, with a froth scraping rate of 15 s. Process water was added incrementally during the test to maintain a constant cell level for the duration of the test.

4. Aerosol methodology development

4.1. Equipment specification and design

4.1.1. Venturi nozzle

The major challenge of procuring a venturi nozzle was finding one of a sufficiently small diameter to be used for aerosol tests. A venturi nozzle was ultimately purchased from an online supplier specialising in "Barbecue replacement parts ", and had the specifications listed in Table 2. The Venturi tube was used in conjunction with a Watson & Marlow 100 series pump, to supply liquid using positive displacement (PD). The schematic representation of the Venturi & PD Pump arrangement is presented in Fig. 1.

4.1.2. Nebulizer

The nebulizer used for the aerosol tests was the Tekceleo Micronice® Nebulizer. This device was specifically designed for use in pharmacology applications, where special care was taken to make sure the nature of the liquid being atomised was not significantly altered. The process therefore does not require elevated temperatures, pressures or pumping.

Table 2. Venturi tube manufacturer specifications

Specification	Value
Material	Polyvinylidene fluoride (PVDF)
Outer Diameter of Inlet and Outlet	1/4 in
Outer Diameter of Air Inlet:	1/8 in
Input Pressure	2 – 3 kg/cm
Output Pressure	0 – 1 kg/cm2
Water Output	0.05-0.25m^3/h

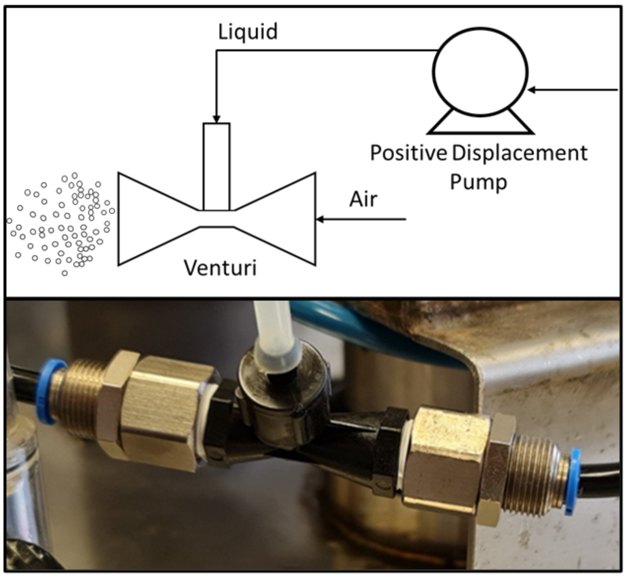

Fig. 1. Gas/Liquid venturi nozzle, with a peristaltic pump propelling the liquid

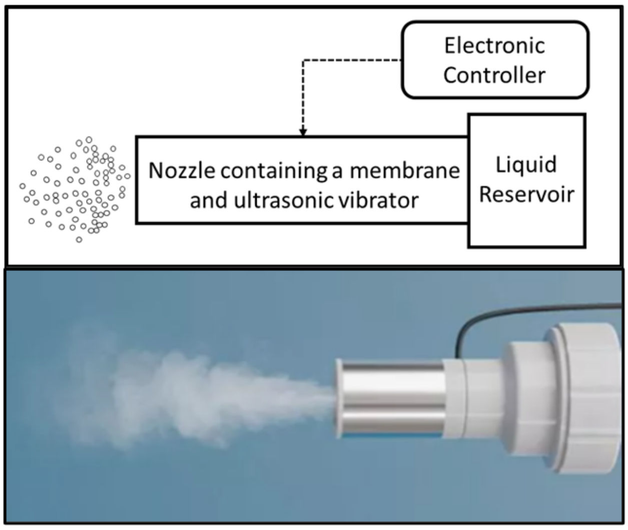

Fig. 2. Tekceleo Micronice® vibrating mesh nebulizer

The device operates by applying ultrasonic vibration to the surface of a micro-perforated membrane. The surface tension of the liquid therefore allows it to be extracted into a cloud of droplets upon membrane contact. The size of the droplets is therefore directly determined by the size of the membrane pores. The device used in this work had a pore size of 5 μm. The device is fitted with an electronic controller that allows for the precise manipulation of aerosol delivery speed and volume. The 5 μm droplet device is rated to produce a flow rate of 0.8 ml/min and holds a maximum liquid volume of 10 ml.

4.2. Calibration

To ensure both consistent and reliable collector dosage, both the nebulizer and the venturi/pump combination were calibrated. Brisbane tap water was used in both calibration tests. In the case of the venturi & PD pump arrangement, the pump was set to different speeds, with the effluent collected from an open-ended pipe. It was assumed that the backpressure head from the flotation cell would have no significant effect on the flow rate. For each pumping speed, the effluent was collected in an evaporating dish and periodically weighed, with both liquid mass and collection time used to verify the flow rate.

In the case of the nebulizer, the effect of backpressure from the flotation cell on the flow rate measured was uncertain. Therefore, the test was conducted by dosing the liquid into the flotation cell as per standard operation. A known mass of liquid was loaded into the delivery chamber and the nebulizer was then run at various speeds while the time taken to nebulise all the liquid in the chamber was recorded.

The calibration curves for both testing methods are represented in Fig. 4. The data show that the delivery of reagents using a positive displacement pump is very stable and consistent. The relationship between speed and dosage is linear, with a coefficient of determination (R2) of 0.99. The maximum flow rate achieved was approximately 0.4 g/min of collector solution.

On the other hand, the nebulizer delivery was less stable than that of a positive displacement pump, with an increasing degree of fluctuation at dosage speeds exceeding 60%. Nonetheless, the calibration curve was still highly linear with the corresponding coefficient of determination (R2) of 0.93. The maximum flow rate achieved was approximately 1 g/min of collector solution.

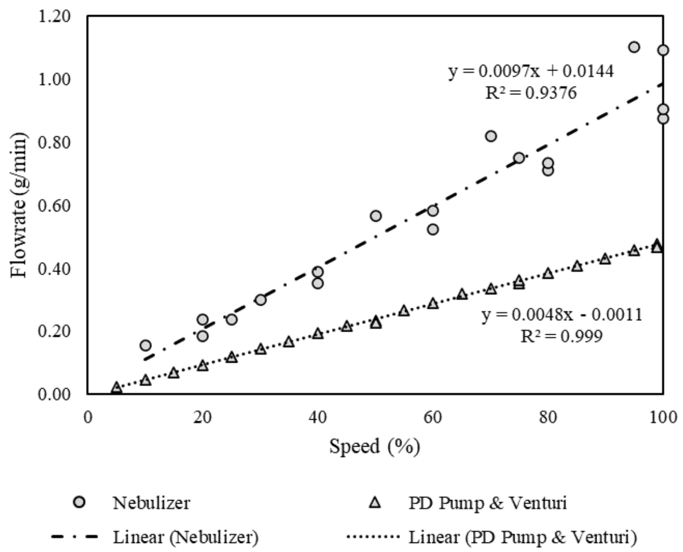

Fig. 3. Calibration curves for both the Nebulizer and the Venturi and positive displacement (PD) pump combination, as a function of both nebulizer and pump speed settings

4.3. Dosage considerations

One of the differences between the conventional collector dosage mechanism and aerosol collector addition is that it takes place continuously throughout the duration of the test, while in conventional collector addition, the reagent is added entirely up-front.

Therefore, additional considerations are required to evaluate how collector dosage is handled for a given test. The calibration tests have demonstrated that the maximum flow rates of collector solution that can be produced are relatively low (1 g/min for the nebulizer and 0.4 g/min for the venturi & and

PD pump combination). While the PD pump can produce a very stable flow across the entire speed range, the nebulizer flow begins to fluctuate when operated above 60% speed output.

Therefore, to ensure that the nebulizer delivery rate is maintained within a stable range, the concentration of the collector solution placed within the delivery chamber needs to be altered. The tests performed in this work used a consistent collector dosage of 5 g/ton, achieved through a combination of different addition methods, addition rates and collector solution concentrations as summarised in Table 3.

Table 3. Summary of collector addition parameters for the three dosage methods

Parameter	Batch	Nebulizer	Venturi
Overall SIBX dosage (g/ton)	5	5	5
SIBX solution concentration (ppm)	600	600	1200
Delivery Setting	-	54%	56%
Delivery rate (g/min)	Added all at once	0.5	0.3
Total solution mass dosed per test (g)	8.13	8.13	4.06

When higher reagent dosages are required, the collector solution concentration can be increased to compensate for the low addition rates. The relatively low solution concentrations used in this work mean that the full range of collector dosages typically seen in base metal sulphide operations (1 – 100 g/ton) can be easily achieved using this methodology.

4.4. Installation

Once both the nebulizer and the venturi nozzle were calibrated, they were fitted within the air supply line of the flotation cell, as shown in Fig. 4 A and B respectively. The Venturi was simply fitted into the airline using standard pipe connectors. A PVC T-piece was adopted to fit the nebulizer nozzle, which was similarly connected to the airline using standard pipe connectors.

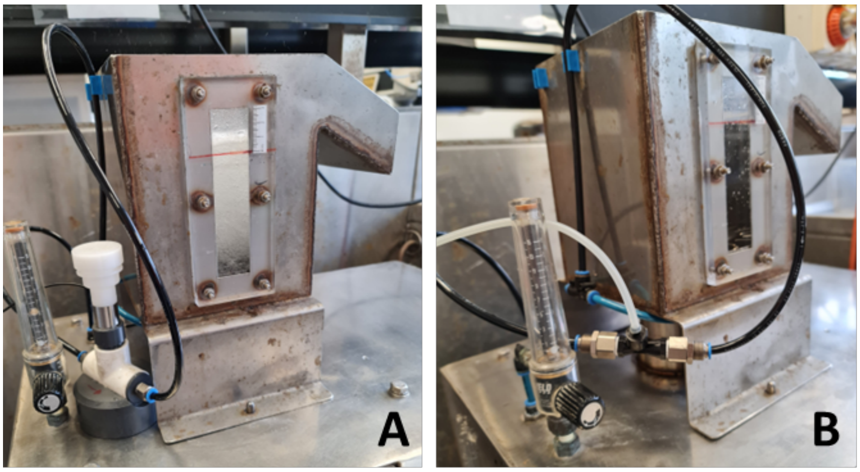

Fig. 4. Images showing the installation of (A) the nebulizer and (B) the Venturi into the airline of the flotation cell.

4.5. Safety testing

Flotation collectors, particularly those used for base metal sulphide applications, tend to be highly toxic. Exposure can irritate the eyes skin and respiratory tract, as well as cause acute poisoning effects including tremors, prostration, dyspnoea, cyanosis and vascular collapse[1].

The addition of these reagents in aerosol form poses a potential risk of inhalation if any of the reagent droplets escape the flotation cell through the top of the froth phase. For this reason, it is important to evaluate the possibility of flotation operators being exposed to air-born collector droplets.

[1] https://www.rshq.qld.gov.au/safety-notices/mines/xanthates-in-mining-update#

The safety evaluation was performed by modifying and adapting a standard mask fit testing procedure. Gas mask fit testing is required by the Australian New Zealand Standard AS/NZS1715 . In this procedure, a good fit of a respiratory mask is tested by placing a plastic hood over the wearer's head, while they are wearing a mask. A bitter-tasting solution (FT-32 Bitrex) is nebulised inside the hood. While the solution has an unpleasant taste, it is non-toxic and has no harmful impact on the test subject. The mask wearer is then able to detect a bitter taste if the mask is not properly fitted.

Because the QLFT test is qualitative rather than quantitative, a decision was made to only perform it on a system that is most likely to result in collector atmospheric exposure. The nebulizer used in this work is designed to produce very small droplets (5µm) and was deemed to be the method that carries the greater risk. For this reason, it was chosen as the delivery method most in need of safety testing.

The nebulizer device was filled with Bitrex testing solution and dosed into the flotation cell in an identical manner to that of a collector. A flotation cell was used in the same manner as that to perform flotation tests in this work (see Section 3). The solution was delivered to the flotation cell at 100% speed, equivalent to 1.2 mL per minute collector dosage.

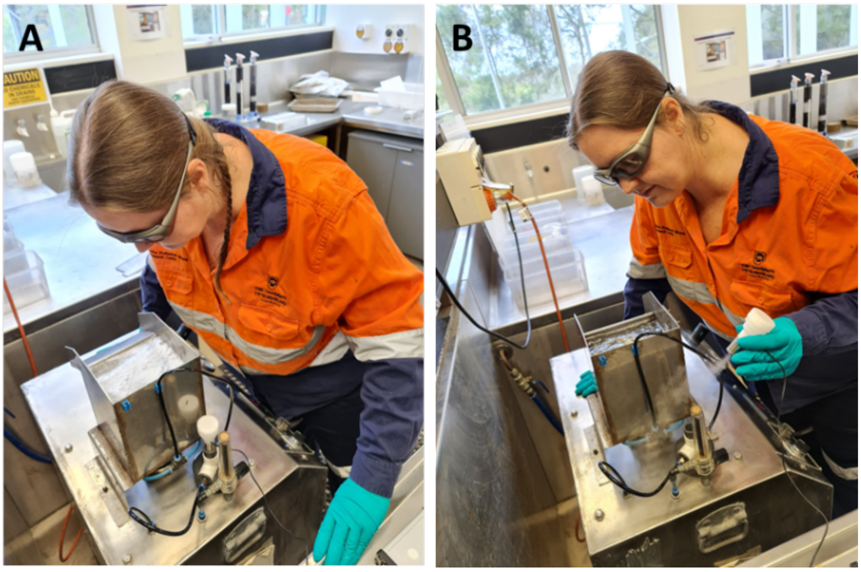

Fig. 5. Safety test using the Bitrex solution (A) nebulized into the flotation cell, (B) nebulised into the air next to the flotation cell as a control.

The "mock" flotation test was then run for the full duration of 15 minutes. During that time the operator held their face over the flotation cell in a manner illustrated in Fig. 5A, to see if any bitter taste could be detected. As a control measure, the nebulizer was withdrawn from its pipe connector at the end of the flotation test, releasing the Bitrex solution into the atmosphere near the flotation cell, as illustrated in Fig. 5B.

Throughout the test when Bitrex solution was nebulised into the flotation pulp, no bitter taste could be detected. On the other hand, the operator detected the bitter taste immediately upon release into the atmosphere during the "control" test. This indicates that no collector droplets are likely to escape the flotation froth into the surrounding atmosphere, causing harm to the flotation operator. Based on this result, the aerosol collector addition method was deemed sufficiently safe to proceed with detailed laboratory testing to determine the efficacy of this new methodology.

5. Proof of concept testing

The flotation tests were performed using three different reagent addition methods: conventional batch collector addition, aerosol collector addition using a venturi and PD pump combination and aerosol collector addition using the nebulizer. It is important to note that the objective of these tests was not to rigorously evaluate differences between the results obtained with each methodology. The objective is twofold:

- Determine if the aerosol collector addition methods can produce a realistic flotation outcome.
- Gauge the usability of the method in terms of its complexity, efficacy and potential for scale-up.

Once both of the above have been established, a statistically designed test campaign can be conducted at a later date to rigorously evaluate the impact of aerosolising the collector on flotation performance.

5.1. Flotation outcomes

The results for copper recoveries as a function of time for all three collector addition methods are presented in Fig. 6. The conventional "batch" addition test was performed in duplicate to test the repeatability of the test procedure. The results show that both repeat tests are in close agreement, demonstrating a high degree of reproducibility.

The results also show that in all cases, a viable flotation outcome could be achieved. The tests making use of aerosol addition techniques, both nebulizer and venturi, showed significantly slower flotation with lower recoveries at the start of the test. This is expected, as the flotation pulp collect significantly more collector at the start of the test when a batch addition method is utilised. However, in all three cases the results showed highly comparable final recoveries in excess of 90%.

The grade/recovery relationship in this system for the three testing methods is presented in Fig. 7. The results show that while comparable recoveries were achieved, the aerosol methodologies result in considerably higher concentrate copper grades.

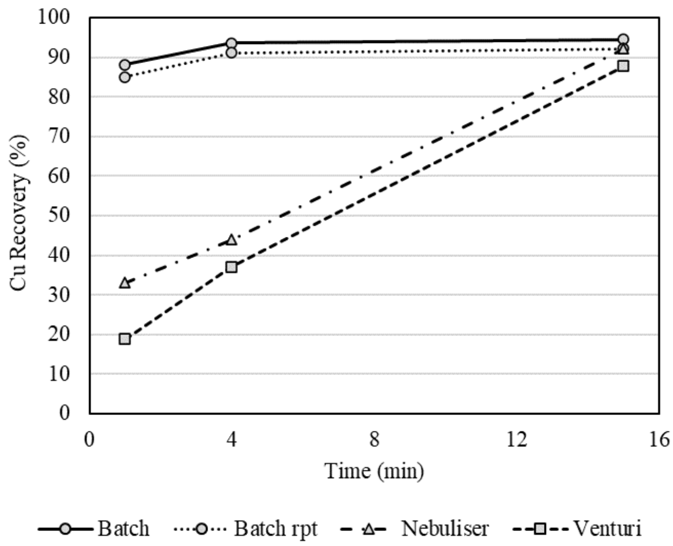

Fig. 6. Time versus recovery curves for three different collector addition methods

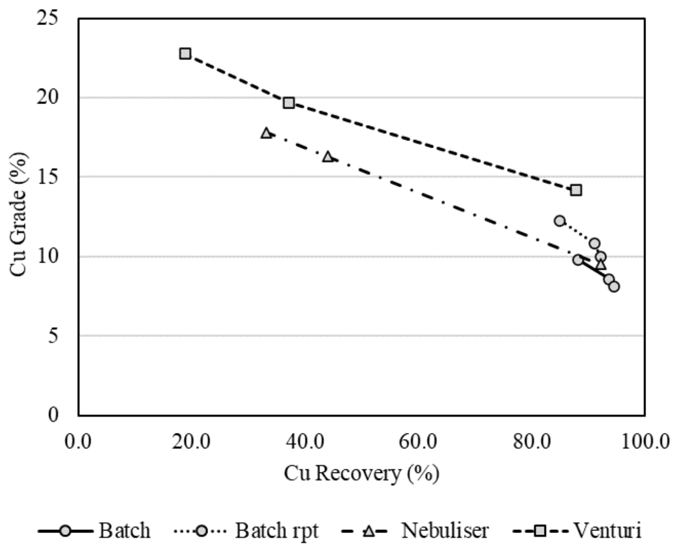

Fig. 7. Grade versus recovery curves for three different collector addition methods

It is important to note that the tests presented in Fig. 6 and 7 were designed purely as a proof of concept. The data presented in this work is not sufficient to optimise flotation performance using these methods, nor to determine the statistical significance of the differences between conditions. However, the limited data clearly illustrate that the addition of collector by means of an aerosol using both a commercially available nebulizer as well as a simple venturi system are able to produce a flotation outcome within reasonable range.

5.2. Ease of use considerations

The flotation results presented have demonstrated that the use of both the venturi and the nebulizer methods can produce reasonable flotation outcomes. However, there are several factors regarding method usability that need to be considered for each.

5.2.1. Complexity and cost

The biggest advantage of using the Venturi system is its simplicity. The installation was very simple and required no specific adaptations. The venturi itself is simple, easy to clean and highly cost-effective whereby multiple units can be purchased at a very low cost. However, the low cost of the venturi pipe itself is counterbalanced by the relatively high cost of a positive displacement pump required for its operation.

On the other hand, the nebulizer carries a significantly higher cost than a venturi piece. However, the laboratory-scale nebulizer model comes with an integrated reagent tank and does not require an additional positive displacement pump. The nebulizer unit is relatively compact and easy to use. The simplicity of the nebulizer in-line installation was comparable to that of a venturi.

5.2.2. Droplet size

One of the biggest drawbacks of using the venturi system in a laboratory setup was the uncertainty surrounding droplet size. When aerosols are generated using a venturi, the aerosol drop size is determined by the overall system pressure. This in turn is determined by the liquid and gas flow rates as well as by the venturi pinch point internal diameter.

The gas flow rate to a flotation cell is determined by the optimum superficial gas velocities required for successful flotation. Therefore, it is not a good operational variable for controlling droplet size. It also means that as the gas flow rate is varied as part of the experimental design, it will result in corresponding changes in droplet size. This introduces an additional variable that needs to be taken into consideration when performing flotation tests using aerosol collector addition.

Another limitation is the lack of available venturis in small sizes. The best way to ensure that a sufficient pressure drop is achieved for a fixed gas flow rate is to minimise the venturi internal diameter. The venturi that was used in this work was the smallest that could be commercially purchased and had ¼ inch internal diameter. The size of the aerosol droplets created by the venturi & PD pump in this work was not quantitatively measured. However, the formation of large droplets within the aerosol stream could be visually observed.

Conversely, the biggest advantage of the nebulizer is its ability to create droplets of a constant size. The droplet size is determined by the fixed pore size of the micro-perforated membrane. The drop size is therefore uniform, even at different speed outputs of the electronic controller. The model used in this work was designed to create droplets 5 µm in diameter. When operated, the observed aerosol stream appeared as a very fine mist, with no visible large droplets.

A drawback of both systems at laboratory scale is a significant degree of droplet coalescence on the tube walls prior to entering the flotation cell resulting in the formation of a few large drops. This is less likely to be a problem in larger systems as the volume to surface area ratio increases.

5.2.3. Potential for scale-up

As discussed earlier, the use of the venturi may not provide the most optimum conditions for small droplet creation in small-scale applications, such as a laboratory batch flotation cell. However, the use of such a simple system may be highly effective when applied to a larger scale, where the dosage system is not constrained by the minimum available venturi internal diameter. When scaled up to industrial-sized flotation cells, the simple design and low cost of venturi pieces will likely be the biggest advantage of this mechanism.

The nebulizer used in this work was the smallest available model, rated to produce a flow rate of up to 0.8 ml/min. However, larger nebulizer models are capable of producing significantly larger flow rates, up to 35 ml/min, sufficient to provide reagent dosage to industrial flotation cells. However, the use of a larger model with a higher flow rate comes with a corresponding increase in droplet size. Alternatively, a single electronic controller can be used vibrate multiple nebulizer nozzles. At this point, it is important to note that the effect of droplet size on the efficacy of aerosol collector addition has not been investigated and the optimum droplet size has not been established. Such large-scale nebulizers do not come with built-in liquid chambers and require the use of a pump, similar to a venturi system.

6. Conclusions and recommendations

Two aerosol collector delivery methods were developed and tested in this work. The first was the use of a small-scale venturi piece in combination with a positive displacement pump. The second was a commercially available nebulizer, developed for pharmaceutical applications. Based on the obtained analysis the following can be concluded:

- The use of a modified QLFT testing procedure demonstrated that aerosol collector delivery methods are safe for the operator with no detectable collector droplets entering the breathable atmosphere.
- Both tested methods were relatively simple and easy to use. However, the nebulizer system has the advantage over the venturi, as it can produce a consistent droplet size of 5 µm. this makes it a more appropriate tool for performing controlled laboratory-based tests. On the other hand, the venturi system is likely more amenable for scale-up in industrial systems.
- The use of both techniques resulted in a reasonable flotation performance comparable to that of a conventional reagent delivery system.

Based on the above conclusions, the following recommendations can be made:

- The nebulizer system is likely more appropriate for use in laboratory flotation tests, and it is therefore recommended that this method be adopted as part of a detailed investigation into the effect of aerosol collector additional on flotation performance.
- The impact of aerosol droplet size on flotation outcomes needs to be considered when conducting future test work on aerosol collector delivery.

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