Oxygen Potentials, Limitations and Enhancement Strategies in Gold Cyanidation: An Overview

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Saim, A. K, Ofori-Sarpong, G., Amankwah, R. K. (2022), "Oxygen Potentials, Limitations and Enhancement Strategies in Gold Cyanidation: An Overview", *Proceedings of the 7th UMaT Biennial International Mining and Mineral Conference*, Tarkwa, Ghana, pp. 1 – 12.

Abstract

Many industrial processes require oxygen to achieve successful operations. In particular, there are a lot of processes and systems in hydrometallurgy where oxygen and its mass transfer kinetics play an essential role. Conventional gold cyanidation requires a sufficient supply of oxygen in order to improve the leaching kinetics. Ensuring consistent availability of oxygen in the leaching system can increase overall plant recovery and throughput. However, low solubility of oxygen in water presents a major challenge to hydrometallurgists. Moreover, the presence of sulphide minerals, electrolytes, as well as elevated temperatures and high pulp densities significantly reduce oxygen solubility, causing oxygen starvation in gold-leaching systems. Therefore, there is always a constant dosage of large volumes of oxygen through pipes into leaching tanks to meet dissolved oxygen demands. Yet, oxygen availability issues have continually persisted in gold-leaching systems worldwide. This paper will focus on current challenges and developments in gold cyanidation regarding oxygen requirement and availability, as well as oxygen dissolution rate enhancement topics that are generally of interest for gold leaching. It is expected that this review will inspire new research for efficient improvements in oxygen mass transfer for leaching systems.

Keywords: Gold, Cyanidation, Dissolved oxygen, Solubility, Oxygen mass transfer

1 Introduction

Considerations such as ore mineralogy, leaching methods, flowsheet development, environmental management and chemical requirements, are very essential when choosing a gold leaching system. In all leaching system requirements, an oxidant and a ligand are needed to oxidize and complex the gold respectively, and the main oxidant in alkaline (pH > 10) and neutral lixiviant (pH 5-9) systems is oxygen (McLaughlin and Agar, 1991; Sparrow and Woodcock, 1995; Pratomo, 2014;). Gold dissolution requires oxygen, according to Elsner's equation (1).

It has been demonstrated that gold leaching is virtually an electrochemical process including anode dissolution of gold and cathode reduction of oxygen and other oxidants (Yang *et al.*, 2010). A pH of more than 10 and an O_2 concentration greater than 6 ppm are required for conventional cyanidation. Under 4 ppm of oxygen, gold dissolution rates are substantially decreased. Oxygen-enhanced operations are those in which oxygen is sparged into the slurry at 12–18 ppm O_2. The more oxygen is present in the solution, the more cyanide can be used effectively to ensure faster and more efficient extraction of gold (Haque, 1992). It suggests that a higher DO level can enhance plant throughput, yet hydrometallurgists have a number of problems when it comes to oxygen mass transfer. As an important reagent in the process of gold extraction, oxygen is limited by its low solubility in water, and therefore, a constant supply of oxygen is required (Filippou *et al.*, 2000). As a result, there is always a need to inject huge volumes of air, which is technically challenging and raises the expenses of processing. In essence, gas-liquid mass transfer, and, in many circumstances, the production of pure or highly enriched oxygen come at a cost. Remote activities with on-site power generation are particularly burdened by oxygen expenses. To improve the efficiency of oxygen transfer, several studies have been done (Bao *et al.*, 2005; Gorji *et al.*, 2006; Gakingo *et al.*, 2020; Ali and

Solsvik, 2021;). The DO concentration in a slurry depends on the rate at which oxygen is transferred from the gas phase to liquid, on the rate at which oxygen is used in order to dissolve gold, and on the rate at which oxygen is consumed by the oxygen consuming species present in solution. Moreover, the hydrodynamic parameters in the leaching tanks have a significant impact on the gas-liquid mass transfer during a leaching operation (Deschênes, 2016). Likewise, a reduction in dissolved oxygen can also be induced by galvanic interactions between sulphide minerals and grinding media types, making cyanide gold leaching more challenging (Rabieh *et al.*, 2017, 2018).

$$4Au_{(s)} + 8NaCN_{(aq)} + O_{2(g)} + 2H_2O_{(l)} \rightarrow 4Na[Au(CN)_2]_{(aq)} + 4NaOH_{(aq)} \quad (1)$$

To overcome the above challenges, often a pre-oxidation process is implemented prior to the gold cyanidation by injecting extra oxygen (Ellis and Senanayake, 2004; Feng and van Deventer, 2007). The added oxygen dissolves and participates in the gold cyanidation as an oxidant, and increasing their concentration enhances the forward reaction rate, thus more production of $Au(CN)_2^-$ as shown in Equation 1 (Kim and Ghahreman, 2019). Oxygen is also employed to boost gold extraction in the case of cyanidation facilities processing gold ores containing refractory sulfides, during the pre-oxidation stages. Without pre-oxidation at higher dissolved oxygen levels, the gold cannot be amenable to cyanidation at a cost-effective rate, and thus pre-oxidation of the ore has been a crucial factor in current leaching circuits (Li *et al.*, 2009; Levasseur *et al.*, 2016; Nunan *et al.*, 2017).

As oxygen availability and solubility has always been a crucial problem in gold leaching processes, a pressing need exists for better oxygen supply and dissolution techniques in gold cyanidation systems. This paper will focus on current challenges and developments in gold cyanidation regarding oxygen requirement and availability, as well as oxygen dissolution rate enhancement topics that are generally of interest for gold leaching. First, the factors that affect oxygen solubility are discussed; then oxygen requirements during pre-oxidation as well as the cyanidation stages are considered. Finally, recent approaches including effective auxiliary oxidants and devices that enhance oxygen supply and dissolution rates for effective gold leaching are highlighted.

2 The solubility of oxygen in multi-phase/leaching systems

Oxygen is an important reagent in hydrometallurgical process that is frequently considered for the pretreatment or leaching of ores at elevated or ambient temperatures and pressures. When it comes to leaching at ambient or high working temperatures, oxygen solubility in the aqueous phase influences the amount of oxidant available. However, the solubility in water is very low, and this is limited by several factors. Therefore, mechanically agitated three-phase slurry reactors should consider the impacts of physical gas, liquid, and solid interactions, and this should be highlighted since such phenomenon mostly prevails in ore pre-oxidation or leaching systems (Neale and Pinches, 1994; Altayeva *et al.*, 2021). The oxygen transfer rate is determined by the liquid film mass transfer coefficient (k_L), the interfacial area for mass transfer (a), and the difference between saturation and dissolved oxygen concentrations (C* and C) according to Equation 1:

$$Oxygen\ Transfer\ Rate = \frac{dC}{dt} = k_L a(C^* - C)$$

Multi-phase (gas-liquid-solid) reactor development has been a focus of many researchers in order to improve mass transfer performance (Ledakowicz *et al.*, 1985; Neale and Pinches, 1994; Pitault *et al.*, 2005; Weist *et al.*, 2009; McClure *et al.*, 2018; Ho *et al.*, 2020). An important aspect to be considered in describing the oxygen solubility performance is the behavior and influence of solid particles present in the leaching tanks (Chen *et al.*, 2013). For years, researchers have been intrigued by the "particle effect" that solid particles have on oxygen mass transfer (Zhang *et al.*, 2013, 2015; Petříček *et al.*, 2018; Iwamura *et al.*, 2020; Lakhdissi *et al.*, 2020; Mejri and Mansour, 2021). In general, a higher solid content would result in a lower volumetric mass transfer coefficient as the slurry viscosity would increase. An increase in volumetric mass transfer coefficient values were seen for stirrer configurations with a low particle concentration, whereas an increase in particle concentration resulted in the opposite (Mills *et al.*, 1987; Van Weert *et al.*, 1995; Kiełbus-Rąpała and Karcz, 2009).

It has been shown that the type of particles present in the solution can also strongly influence the oxygen solubility rate (Garcia-Ochoa *et al.*, 1997; Littlejohns and Daugulis, 2007). A wide range of bubble hydrodynamics and oxygen mass transfer parameters were studied by changing the shape of the solid media used (a ring, sphere, cylinder, and square). With the addition of solid media, the oxygen transfer coefficient in the bubble column reactor was increased by 31% – 56%, and this increase was greater at higher solid loading due to its higher effective surface (Figure 1). The presence of the media also resulted in smaller bubble size distribution (Sastaravet *et al.*, 2020).

High electrolyte concentrations are frequently found in hydrometallurgical systems. Oxygen solubility in water has been studied over a wide range of temperatures and pressure mostly encountered in leaching operations, and it was found that the inclusion of mineral solutes and electrolytes in industrial leaching solutions will influence oxygen solubility compared to pure water (Weissenborn and Pugh, 1996; Tromans, 1998). In agitated tanks, oxygen solubility increases linearly with increasing temperatures in the range of 0–35°C (Downing and Truesdale, 2007). As the temperature rises, solids increase the propensity of mass transfer, thus solids have a diminishing influence on the mass transfer when the temperature rises (Zhang *et al.*, 2019).

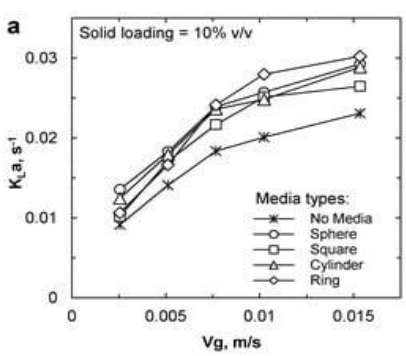

Fig. 1 Overall mass transfer coefficient (K_La) in bubble column reactor of each solid media type with: (a) superficial gas velocity (Vg) and (b) solid loading (Sastaravet *et al.*, 2020)

3 Pre-aeration and gold cyanidation

Cyanidation is typically conducted at a pH of over 10, with an O_2 concentration of at least 6 mg/L. Difficulty dissolving gold occurs when DO concentrations fall below 4 mg/L. A higher DO concentration will, on the other hand, result in a faster gold dissolving rate. O_2 enrichment is achieved by sparging oxygen into the slurry to produce 12-18 ppm O_2. A higher DO concentration would enhance plant productivity. oxygen is utilized to maximize plant throughput by boosting gold extraction in the case of cyanidation facilities that treat gold ores containing low refractory gold ores.

A shortage of dispersed oxygen may prevent the gold from leaching, reducing the amount of gold that can be recovered from the ore (Kondos *et al.*, 1996). For instance, it was found that up to 30% of gold reporting in the tailings was still leachable and was not being recovered due to process kinetics, specifically due to the low concentration of DO in the slurry in the initial tanks of the cyanidation (Nunan *et al.*, 2017). The presence of sulphidic minerals in gold ore cyanidation is also known to cause considerable oxygen consumption. Therefore, pre-oxidation before the introduction of cyanide has been the common practice to increase gold leaching kinetics. With pre-oxidation, the processing time can be reduced by accelerating leaching kinetics in order to decrease processing costs. Maintaining a high amount of DO in the leach pulp is critical to the successful completion of the gold dissolution process and reduction in cyanide usage (Nabiulin *et al.*, 2017; Ariyanti and Syaifuddin, 2019). This section discusses the key sources of the oxygen supply, including atmospheric air, pure oxygen, hydrogen peroxide, and ozone.

It is believed that pre-aeration serves two purposes: (i) to oxidize and disintegrate sulphide minerals to expose encapsulated gold, and (ii) to passivate the sulphide minerals by making the surface less reactive in the cyanidation process. This increases oxygen saturation in the circuit and increases metal recoveries as well as cuts down on leaching costs by decreasing the amount of cyanide required. For example, during a 24 h sulphide gold-silver ore leaching study, lead nitrate, H_2O_2, and aeration using an air pump were investigated in order to reduce the consumption of NaCN (3.35 g/dm^3). Lead nitrate addition with aeration resulted in a decrease in metal extractions, while H_2O_2 additions alone or in combination with aeration did not reduce cyanide use. For this reason, it was decided to examine the effects of pre-aeration followed by cyanidation. When pre-aeration was applied for 4 hours before 12 h of short-term leaching, 92.0% Au and 90.5% Ag were extracted, with a decreased NaCN consumption of 2.44 g/dm^3 (Aydin *et al.*, 2015).

In fact, gold recovery in these leach systems can be economically catastrophic if the pre-oxidation stage is not limited by carefully controlling the pre-oxidation conditions. For example, sulphide oxidation processes under aggressive pre-oxidation circumstances have been demonstrated to not only raise temperatures but also produce cyanicides, which are compatible with observed high cyanide consumption and low DO content. The pre-oxidation stage and its influence on downstream operations at the Kibali Gold Mine Processing Plant, which uses ultrafine grinding and a two-stage pre-oxidation process revealed circuit stabilization by both the cyanide demand and concentrate leach residues after the circuit was completely reconfigured by DO and pH stabilization. In addition, the pre-oxidation DO and pH gave the strongest connection with each other, as well as cyanide consumption and concentrate leach residue grade as shown in Figures 2 and 3 (Mahlangu *et al.*, 2020). A lower concentration of DO resulted in a high amount of gold reporting to the tails residue.

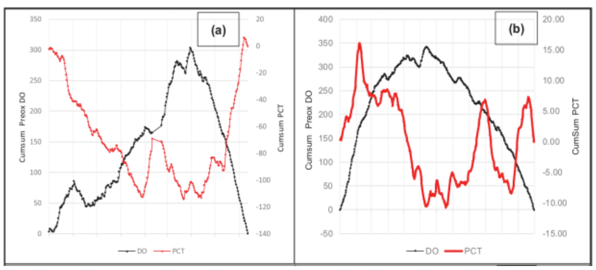

Figure 2 Effect of pre-oxidation dissolved oxygen: (a) Period D – Oct 2015 to July 2016; (b) Period G – Jan to Dec 2018 on the concentrate leach solids residue (pumpcell circuit tails (PCT)).

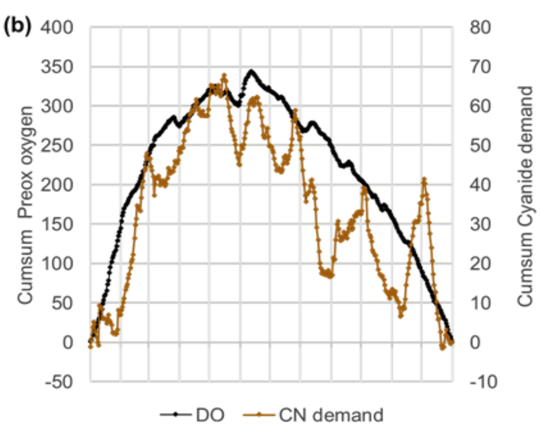

Figure 3 Reactivity number or oxygen demand survey plots for the concentrate pre-oxidation circuit (September – October 2017).

3.1 Air and Pure Oxygen Sparging

It is shown that solubility can be increased by increasing the driving power i.e. oxygen partial pressure in gas fed to the leach pulp. Solubility increases with increasing oxygen partial pressure in the gas stream, according to Henry's gas law. For air as the oxidant, the amount of cyanide that is lost by the removal of HCN gas from the solution increases owing to increased gas flow rates, as the oxygen demand grows. Besides, when air is pumped into the pulp, it creates a lot of foam, which is a significant problem. It is possible to get higher partial pressures of O_2 by adding pure oxygen to the air or gas stream. Therefore, extensive pure oxygen dosing is required for the cyanidation of refractory gold ores, which employs methods such as Carbon in Leach (CIL) and Resin-in-Leach (RIL) as well as laboratory bottle roll leaching. More so, operations employing very salty process water to treat well-oxidized ores have also found it advantageous to supplement atmospheric oxygen.

Oxygen consumption and efficiency, and rate of oxidation as a function of the initial DO were measured during the pre-aeration stage. The type and concentration of sulphide species in the ore affected the oxygen consumption for the superficial oxidation of the particles, ranging from 5 to 150 g O_2/h/t (Jara and Bustos, 1992). From plant measurements, 8.6% and 0.6% were the oxidation efficiency of oxygen and air, respectively, and the rate of oxidation increases remarkably with the level of DO for unoxidized sulphides (Jara and Bustos, 1992).

For instance, GOLDOX hydrometallurgical method injects regulated volumes of industrial oxygen into one or more leach tanks using specially built and positioned lance and nozzle assemblies. Oxygen is provided in the form of liquid. Through freshly constructed stainless steel pipes and a flow control panel, the leaching tank was supplied with oxygen. As a result, the air compressor was turned off, and all air piping was removed from the leaching tanks. Leaching with typical air injection was used compared to leaching with pure oxygen. The average residue grade (%) dropped from 1.91 to 1.69 when pure oxygen was used (Wei and Von Scheele, 2017). Leaching gold with oxygen against leaching with air is shown in Figure 9. DO level was determined to be 0.45-1.72 mg/L in the air bottle, which is much below the saturation value of dissolved oxygen (8.2 mg/L). Particularly, the sulfides in the gold concentrate were using a lot of oxygen in the leaching bottle. However, the bottle with oxygen injection had a DO level greater than 20 mg/l (Figure 4) (Zhongling *et al.*, 2015).

Sparging straight into the leach tank is the most common method of delivering oxygen, and the sparge is generally positioned to optimize mixing. Oxygen is injected into the slurry feed line in some operations to take advantage of greater pressures and turbulence (Bodnaras *et al.*, 1993). Using the enhanced pre-oxidation technique for the pyrrhotite-rich gold ore of Bounty Gold Mine illustrated how gold recovery rates increased while reagent consumption rates decreased. With the installation of a pipe reactor and an oxygen injector from Multi Mix Systems, it was possible to reach a DO level of 20 mg/L with less amount of oxygen (Ellis *et al.*, 2002). Ideally, gaseous oxygen is typically chosen over other strong oxidizing agents because it may be produced on-site and is less expensive than the alternatives if gas dispersion is effective (Lunt and Weeks, 2016).

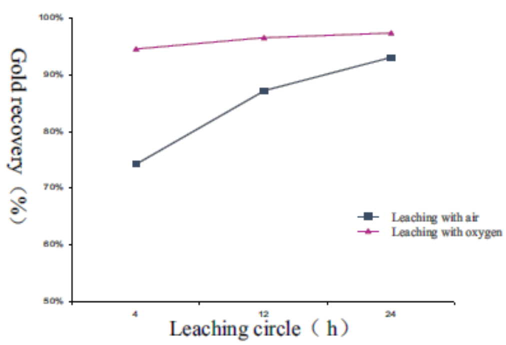

Figure 4 Compared oxygen with air in bottle roll leaching (Zhongling *et al.*, 2015).

3.2 Auxiliary Oxidants

Hydrogen peroxide

Oxygen is commonly used in gold leaching, but its limited solubility in water has certain drawbacks, and hydrogen peroxide has thus been investigated as a viable supplement or replacement. The process intends to introduce oxygen in a liquid form. In fact, oxygen injection in the form of liquid oxygen has proven to be the most popular of the other choices, when leaching plants are seeking to enhance DO levels. The decision to use H_2O_2 instead of air is motivated by the fact that the presence of physical DO in the pulp is one of the most critical requirements for the rapid dissolution of gold (Kudryk and Kellogg, 1954; Cornejo and Spottiswood, 1984).

The use of this oxidant, if properly regulated, can enhance gold extraction rates and reduce cyanide use (Loroesch *et al.*, 1989; Monhemius, 1992; Gurman *et al.*, 2015). When DO is low (in situations of treating ores with a high oxygen demand), H_2O_2 may function as an extra oxidant, especially since it can break down to oxygen, a process that can be catalyzed by the ore (Dai and Breuer, 2013). It is found that adding 60 L/h of concentrated H_2O_2 at the rate of 150 t/h of dry ore during pre-oxidation resulted in an increase in the DO content from an average of around 1.0 to 7.2 mg/L. This also resulted in a decrease in NaCN usage from 0.52 to 0.40 kg/t of ore, and gold recovery improved from 91.3 to 92.5% (Nunan *et al.*, 2017). In another study, it was found that adding hydrogen peroxides maximized gold dissolution, so long as the redox potential was kept in the negative range (Stoychevski and Williams, 1993). In a cyanide leaching process, H_2O_2 (15 g/L) was shown to increase Au and Ag recoveries by shortening the leaching time (Arslan *et al.*, 2003).

It is possible to boost the cyanidation rate by adding large quantities of hydrogen peroxide, but sometimes at the possible cost of higher cyanide decomposition by hydrogen peroxide (Guzman *et al.*, 1999; Baharun *et al.*, 2020; Hou *et al.*, 2020). Particularly, in the presence of hydrogen peroxide concentrations over 0.01 M, the free cyanide concentration dropped, which was ascribed to the production of the cyanate anion (CNO^-) (Fungene *et al.*, 2018). However, despite significant laboratory research into its use in the oxidative leaching of minerals, it has received a very limited practical application, given its instability, relatively poor reactivity except at high concentrations and its cost (Nicol, 2020). Aside from the cost of this reagent, there are several important aspects of the chemistry of its use that have not been fully appreciated nor understood (Yazıcı, 2017; Wang *et al.*, 2020).

Ozone

For the treatment of gold ores, the use of ozone gas (O_3) may be a potential alternative because of its high degree of oxygenation. Laboratories have successfully used ozone's unique chemical characteristics to pre-oxidize refractory ores. Due to the high capital and operational expenses connected with ozone production, ozone has never been used on a commercial basis. Ozonation as a technique for treating refractory ores has been resurrected by recent advances in ozone generation and contactor systems. The obvious advantages of ozone treatment over other pre-oxidation treatments (such as oxygen or hydrogen peroxides) include faster deactivation of the sulfur matrix and larger savings in later cyanidation processes. To test the effects of ozone pre-treatment, Agnico Eagle's LaRonde mine flotation tailings were mixed with process water, and ozone treatment rendered the material surface and the solution inactive. This led to significant savings in the amount of cyanide used and the amount of thiocyanate formed throughout the process (Levasseur *et al.*, 2016).

Ozone oxidation treatment, according to data appears to have great potential for optimizing ore processing, which is becoming challenging using existing industrial approaches (Li *et al.*, 2009; Rodríguez-Rodríguez *et al.*, 2018). According to the results, gold and silver extraction increased by at least 15% while cyanide usage also decreased when ozone was used (Pedroza *et al.*, 2012). Ozone pretreatment enhanced gold recovery by 23% compared to traditional cyanidation (only 9%) (González-Anaya *et al.*, 2011). High gold and silver extraction were obtained by pre-oxidation with ozone by contacting the ore three times with ozone-saturated water or direct addition of ozone to the mineral slurry (Figure 5). Gold and silver recovery time was decreased from 40 to 24 h by using direct pre-oxidation with ozone (Elorza-Rodríguez *et al.*, 2006). Additionally, the oxidation rate of ozone is found to increase with temperature, but it drops at higher temperatures due to a reduction in the solubility of O_3 in water (Viñals *et al.*, 2006).

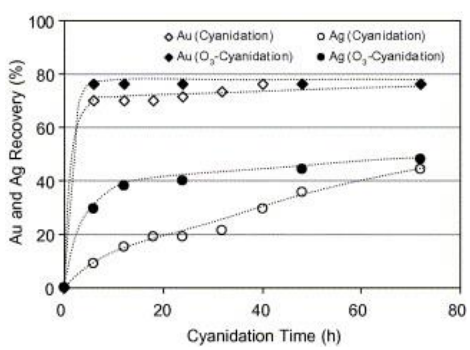

Figure 5 Gold and silver recoveries of mineral A when treated by direct ozone addition and cyanidation. (Elorza-Rodríguez *et al.*, 2006)

4 Methods to Improve Oxygen Delivery in Agitated Leaching Tanks

Agitation and air sparging are employed in numerous CIL plants to counteract the consequences of oxygen deprivation in the system. Even though the cyanidation process cycle can be expedited by using pre-oxidation methods, it is still a lengthy process. Generally, leaching refractory ores for 24 h or longer is the requirement in order to get satisfactory gold recoveries greater than 90%. Significant efforts have been made to enhance the essential oxygen supply, mostly via the use of sophisticated methods for gas dispersion or by replacing compressed air with pure oxygen. The oxygen transfer rate being a function of bubble size is increased accordingly when smaller bubble sizes are introduced (Bredwell and Worden, 1998; Bouaifi *et al.*, 2001; Juwana *et al.*, 2019; Mueller *et al.*, 2020). As a result, the performance of slurry column reactors is strongly influenced by gas distributors (Ashley *et al.*, 1992; Dai *et al.*, 2004; Liu *et al.*, 2019; Li *et al.*, 2021;). Researchers are finding better knowledge of hydrodynamic characteristics and oxygen mass transfer processes by investigating design factors that characterize the operation and transport phenomena of oxygen gas distributors within cyanidation slurry tanks (Ellis and Senanayake, 2004).

Efforts have also been invested in the development of efficient devices that could enhance oxygen transfer rate and dispersion at a reduced bubble size (Lunt and Weeks, 2016). The proponents of these technologies claim that it improves DO concentration, reduce oxygen consumption, and improve the gold-leaching rate and recovery. These devices have been tested at the pilot and industrial scale. Briefly, these devices utilize the principle of cavitation, where micro and picobubbles are created. The cavitation process propagates stress at the inter-phase bubble particles to increase the local pressure and temperature, and once produced microbubbles collapse (Suslick *et al.*, 2011; Gągol *et al.*, 2018;). This occurs when the local pressure falls below the saturated vapor pressure of the liquid (Lugli and Zerbetto, 2007).

Cavitation was formerly thought of as a destructive and unwelcome process that might destroy pumps, pipelines, valves, and, in some cases, whole tanks. Research on cavitation processes has been ongoing over the decade, and it has been successfully implemented to improve various physical, chemical, and biological processes. By using hydrodynamic cavitation devices, the utilization of nano/microbubbles to more efficiently increase oxygen supply has already found practical applications (Oliveira *et al.*, 2018). In addition to improving the leaching kinetics, these devices have been proven to minimize processing costs and time (Carpenter *et al.*, 2017).

4.1 Filblast reactor

The Filblast aeration technique was developed by Atomaer Pty. Ltd. in Western Australia (Sceresini and Nguyen, 2000). With this method, gold ore pulps had much greater amounts of DO that could not be produced with a bubbler under identical circumstances, which led to faster oxidation and shorter residence periods in the pre-oxidation step. Oxygen uptake rate into de-aerated water was 600% faster using a Filblast unit with oxygen, and 300% faster when air was utilized. Moreover, the Filblast unit required lower oxygen flow rates for a given DO content, leading to savings in oxygen (Figure 11) (Bodnaras *et al.*, 1993). Testing was done on three different gold mine waste water. The Filblast unit also oxidized oxygen-consuming constituents in the ores faster than the bubbler.

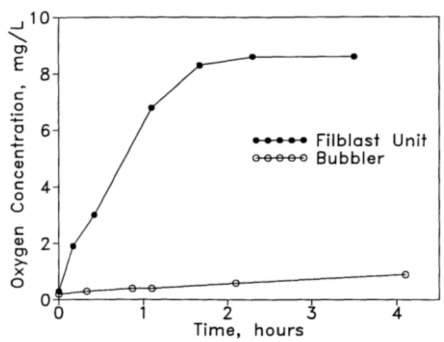

Figure 6 DO Concentration in Pulp During Aeration Tests with Filblast Unit and Bubbler (Gas Flow Rate: 0.75 L/min)(Bodnaras *et al.*, 1993)

A single pass through the Filblast within a short time satisfied over 70% of the oxygen demand of a very reactive gold ore consisting of 40% by weight sulphide minerals, principally pyrrhotite, arsenopyrite and marcasite. Gold extraction increased by approximately 10% and the combined effect of lower reagent consumption and higher gold recovery resulted in a reduction in treatment costs (Sceresini and Nguyen, 2000).

4.2 Aachen reactor

To enhance oxygen mass transfer in the leaching solution, the Aachen reactor has been developed to improve the leaching efficiency of highly refractory ores. Aachen Assisted Leach high shear oxygen dispersion devices coupled with simultaneous addition of cyanide has been used at the industrial scale (Mahlangu *et al.*, 2020). It is employed as a pre-oxidation process before cyanidation. When employing the Aachen reactor, plant observations revealed an average gold recovery increase to 73% from 69% (Mahlangu *et al.*, 2020).

4.3 Jetleach reactor

There is also the Jetleach reactor, as a patented device for enhancing the leaching kinetics of gold ores, which has been in use over the years since 1994. Micro-cavitation is promoted by the Jetleach reactor by impacting two pulp streams against one another at a relatively high velocity with oxygen under pressure. The Jet reactor technique is presented in Figure 7 (Loftus *et al.*, 1997). Using this method, it was demonstrated that free milling gold ore leaching kinetics may be improved. When compared to the standard stirred tank and bottle roll leaching techniques, the reactor demonstrated improvements in gold recovery. It has been proven that when applied to free milling ores, the Jetleach reactor enhanced gold recovery by almost 10% after only 2 h, and it demonstrated the ability to drastically reduce the amount of time necessary for cyanidation processes (Mbayo *et al.*, 2019). Leaching of refractory gold ores from West Africa also saw an improvement by the Jetleach reactor. Compared to the traditional and bottle roll methods, the Jetleach reactor was able to enhance gold recovery by approximately 10% and 15%, respectively (Mbayo *et al.*, 2019).

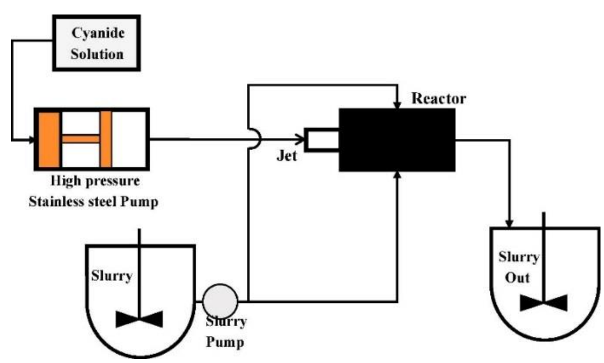

Figure 7 Schematic diagram of the Jet reactor experimental setup.(Mbayo *et al.*, 2019)

4.4 Mach reactor

The patented MACH Reactor technology, which is marketed by Gold Ore is also a cavitation unit that generates nano/picobubbles that nucleate on particles ("GoldOre – Inventors of the MACH REACTOR", 2021). The Mach reactor concept is depicted in Figure 8. A mixing nozzle feeds high-speed cavitating nozzle which then jets into a collecting nozzle before the slurry in the reactor departs. Approximately 5 bar of pressure is used to inject air between each nozzle as shown below (Ross *et al.*, 2019).

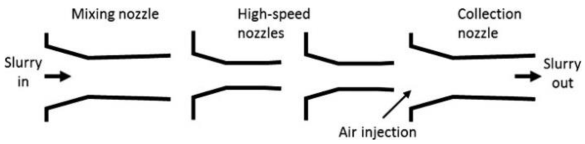

Figure 8 Schematic of Mach reactor (Ross *et al.*, 2019).

The increased oxygen supply in gold cyanidation can be attributed to the concept of particles giving birth to bubbles by these reactors. In deciding which reactor to use for a plant, factors like simplicity of operation and decreased downtime due to blockages or wear should be taken into account, along with scalability, and the fact that the reactor could be used for both pilot and industrial trials. It is obvious that efficient supply and constant availability of oxygen in cyanide gold leaching systems has been the key to ensure faster leaching kinetics, reduce cyanide consumption as well as eventual increase in plant throughput (Mahlangu *et al.*, 2020). However, it is interesting to note in Figure 9 that even after long hours of oxygen dosing, oxygen removal from slurry can be very fast causing oxygen starvation. Particularly, after 3.5 h of aeration, almost a complete removal of DO was observed within 7 mins. This unwanted situation necessitates a constant supply of oxygen throughout the leaching process.

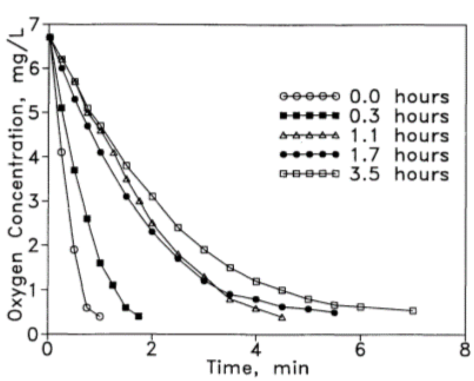

Figure 9 Rate of Oxygen removal from sample pulp as a function of aeration time during Filblast unit test (Bodnaras *et al.*, 1993).

5 Conclusion

The amount and the rate at which gold can be leached depends on the DO levels present. This review has shown that efficient supply and constant availability of oxygen in cyanide gold leaching systems is the key to ensuring faster leaching kinetics, reduce reagent consumption as well as an eventual increase in plant throughput. Ensuring adequate DO concentrations at the pre-oxidation and leaching stages have had significant benefits in plant stabilization. However, the major challenge of oxygen limitation resulting from its poor solubility in water has continued to persist in hydrometallurgical processes including gold cyanidation. Moreover, the presence of sulphide minerals, electrolytes, as well as elevated temperatures and high pulp densities significantly reduce oxygen solubility, which causes oxygen starvation in gold leaching.

For the most part, the gold extraction industry has made significant developments in enhancing oxygen availability during cyanide leaching of gold ores in agitated systems. Persistent dosage of large volumes of oxygen through pipes into leaching tanks is able to increase DO levels to some extent. In practice, the use of pure oxygen instead of air promotes sufficient oxygen levels for gold cyanidation. Both ozone and hydrogen peroxide have shown efficient oxygen enhancement potentials. However, their high cost and instability, particularly hydrogen peroxide, have limited their practical use at the industrial scale.

Furthermore, to enhance the oxygen mass transfer rate into solution, considerable efforts have also been made to develop efficient devices to generate micro/nano/picobubbles based on cavitation. These devices have tremendously improved gold leaching kinetics through effective oxygen dispersion, and they have helped to reduce cyanide consumption. However, constant oxygen injection to create a large number of oxygen bubbles needs long enough and deep enough dispersing in the slurry to provide adequate DO concentration for gold dissolution. In addition, most of the sparged undissolved oxygen tends to escape from the leaching system due to other factors. Currently, in order to achieve a gold recovery rate of more than 90%, the leaching duration must be extended to 24 h or more. More research is therefore needed to develop strategies and technologies to enhance oxygen availability and dissolution rates in order to increase gold recoveries within a shorter residence time at both CIL or CIP plants, without compromising cost, energy and reagent consumption.

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