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Determination of flow patterns in industrial gold leaching tank by radiotracer residence time distribution measurement

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Abstract. The carbon-in-leach (CIL) process is one the most efficient methods of gold recovery from gold bearing ores. The efficiency of the leaching process greatly depends on the flow structure created by mechanical agitation (in some cases air agitation) in the leaching tanks. Residence time distribution (RTD) measurement was conducted in the CIL section of a gold processing plant in order to determine the flow structure in the first tank using the ^{131}I radioactive tracer. The shape of the experimental data revealed that the flow behaviour in the tank was close to an ideal mixer. Modelling of the experimental data, however, revealed that the tank was not behaving as a single perfect mixer, but consisted of two mixing zones. The flow structure in the tank was best described by the "perfect mixers with exchange" model consisting of two mixing zones. The model allowed the determination of flow parameters including the mean residence time, flow rate and volumes of the mixing zones.

Key words: mineral processing • gold ores • leaching • radiotracer • modelling

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Introduction

The process of gold recovery is composed of a sequence of unit operations ranging from ore comminution (crushing and milling) through leaching and finally, the production of gold bullion. Since the discovery of gold, alkaline sodium cyanide solution has been used to recover the metal from its ores. And today, most of the world's gold is recovered with cyanide playing a large part in the beneficiation of the yellow precious metal [17]. Apart from cyanide as the main leaching agent, oxygen plays an important role to speed up the reaction during the leaching process and it has been proven that the rate of dissolution of gold in cyanide solution is directly proportional to the amount of oxygen present. Alkalies, (hydrogen peroxide, calcium oxide etc.), are used to adjust the pH of the pulp to a value between 9.5–11. Thus, preventing the decomposition of cyanide in solution to form hydrogen cyanide gas which is highly toxic to people. The leaching process can be represented by the Elsener equation [19]:

$$4Au + 8NaCN + O_2 + 2H_2O \rightarrow 4NaAu(CN)_2 + 4NaOH \quad (1)$$

In most cases, gold leaching is carried out in a cascade of stainless steel tanks which are continuously stirred. Although air agitated leaching tanks were commonly used in industry, there is preference for mechanical agitation due to lower operating costs [24]. With the goal of achieving optimum performance, the design of these tanks is based on the principle of a perfect mixer, which assumes instantaneous uniformity of reactor content. However, perfect mixing is rarely attained in practice. As a result of the large amount of pulp they hold and the mixing method used, the tanks may exhibit dead and by-passing zones that deteriorate the performance of the process [4, 14]. These malfunctions do not only lower contactor efficiency, but cause deleterious effect on product quality which reduce economic benefit. Additionally, they can pose problems for plant safety and further cause unwanted impact on the environment [20, 21].

Despite the huge impact of the CIL process on gold ore processing and the general economic importance of gold as a metal, systematic studies on the physical phenomena that affect the hydrodynamic characteristics relating to the optimal operation of gold leaching reactors have received much less attention. Therefore, the phenomena occurring in them are not yet entirely understood [3, 5]. In the leaching process, the contact time of the gold ore and cyanide is of prime importance and has a direct bearing on the quality and efficiency of gold recovery. The efficiency of the process depends very much on the degree of mixing in the reactors, where a state of full suspension of the gold particles and cyanide is expected throughout the entire time of residence of the ore slurry in the reactor. Hence, the process efficiency is directly related to the time the slurry spends in the reactor. The distribution of the time it takes for the reactor contents to proceed from the inlet to the outlet is the best indication of flow patterns and mixing properties of any continuous stirred tank reactor (CSTR) [13] and can be conveniently determined from a suitable tracer experiment. The principle of the tracer experiment consists of a common impulse-response method: injection of a tracer at the inlet of a system and recording the concentration-time curve at the outlet. The tracer concentration vs. time at the outlet of the system after normalization is the experimental RTD [26]. Literature review, of hydrodynamic studies of hydrometallurgical reactors in the mineral processing sector, has revealed that contactors of heap and flotation column leaching have received significant attention that have been summarized in many publications such as [3, 6, 13, 15, 16, 18, 23, 26, 29, 30]. However, it is observed that, mechanically agitated CIL gold leaching tanks have received very little attention despite its importance for the comprehension and eventual optimization of this gold extraction method used in many plants around the world.

This observation was also made by de Andrade Lima and Hodouin [5]. In their publication, a study on the hydrodynamics of an industrial gold leaching tank using lithium chloride as a tracer was presented. They analysed liquid samples of slurry taken from the tank for lithium concentration by an atomic absorption spectrophotometer (AAS) to generate the RTD. The investigation was conducted on the primary leaching tank with a nominal volume of 412 m^3 using a solution of 12 kg of the salt dissolved in 40 L of water. They found that the flow structure in the tank was described by a dominant perfect mixer, a series of perfect mixers with cross-flow and a by-pass stream represented by a series of perfectly mixed reactors.

In this study the CIL section of the plant consisted of a cascade of 7 tanks, each with a nominal volume of 3000 m^3. The objective was to investigate the pattern of flow in the first tank using the ^{131}I radioactive tracer. Radioactive tracers are suitable for RTD investigation of systems having large volumes because they have a high detection sensitivity and are, therefore, detectable in extremely low concentrations. Hence the amount of tracer required is small [9, 11].

Experimental

Plant description

The investigation was conducted at the Damang Mine of Abosso Goldfields Limited located in the Western Region of Ghana. The mine operates seven CIL tanks connected in series, each of a nominal volume of 3000 m^3. The flow diagram of the mine at the time of the investigations is shown in Fig. 1. After mining, the

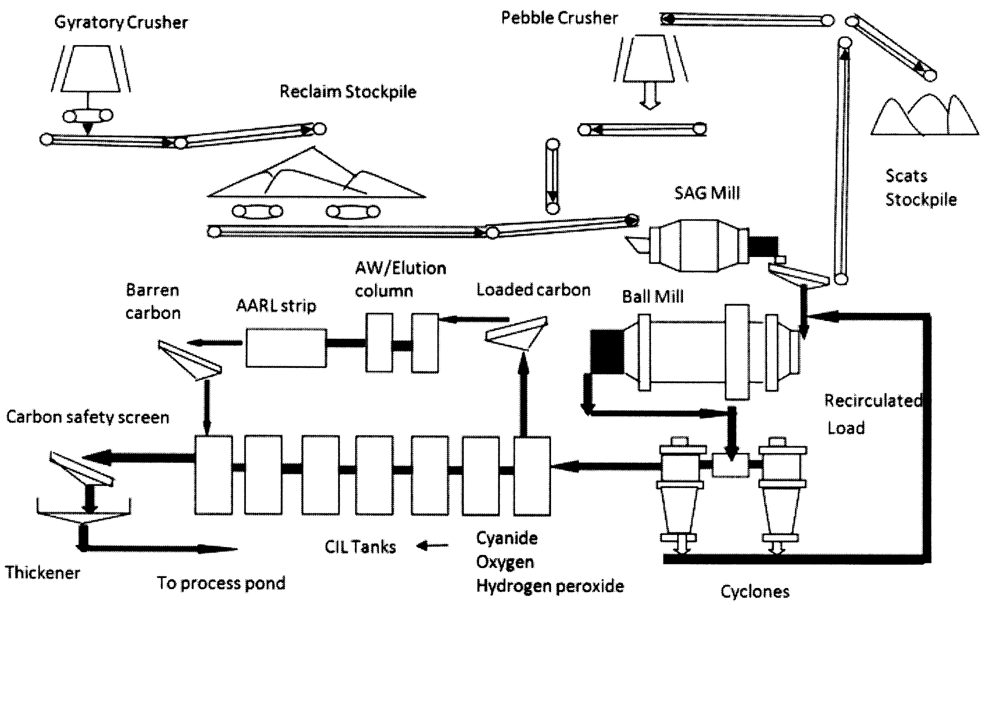

Fig. 1. Flow diagram of gold ore processing at Damang Mine.

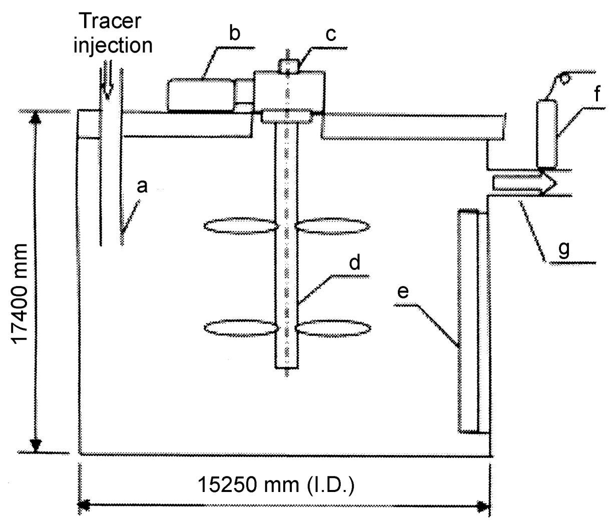

Fig. 2. Schematic diagram of tank: a – inlet pipe; b – motor and drive mechanism; c – sparge sleeve; d – shaft with impellers; e – baffle; f – detector; g – outlet stream.

ore is crushed and ground in semi-autogenous (SAG) and ball mils to form a slurry mixture which is dewatered and thickened in cyclones to increase the pulp density to about 50% solid content. The slurry is then pumped into the first leaching tank through a pipe buried about 1.5 m from the surface.

In order to ensure a state of full suspension of the gold particles and cyanide, each tank is continuously stirred by a mechanical agitator consisting of two impellers spaced at 7 m from one another. Each impeller consists of three blades equally spaced at 120° and mounted on a shaft with bolts. The second impeller is installed at a distance of 4.8 m from the tank bottom. The shaft is hollow with a sleeve at the top for gas (oxygen) inflow into the tank. It is driven by a 90 kW electric motor with a nominal rotational speed of 960 rpm. In each tank, three baffles are set at 120° radially along the tank walls in order to eliminate the effect of vortex so as to improve mixing efficiency. The schematic diagram of the tank is shown in Fig. 2.

Data collection

The tracer consisted of approximately 1.8 Ci of ^{131}I (I-131) which was produced in a nuclear reactor by neutron bombardment of stable tellurium. It has a half--life of 8.02 d with primary emissions of 364 keV gamma rays (81% abundance) and 606 keV beta particles (89% abundance) [22]. The molecular formula of ^{131}I is $Na^{131}I$ [7] meaning that the tracer is in the chemical form of sodium iodide. The success of $Na^{131}I$ as a suitable aqueous tracer for process systems was highlighted by the IAEA [12]. This was also confirmed by Sugiharto *et al.* [27] who successfully determined the flow rate of the aqueous phase in a hydrocarbon transmission pipeline by RTD methodology using an I-131 tracer in the form of sodium iodide.

A property that makes $Na^{131}I$ a suitable aqueous tracer is its slight solubility in water. Nevertheless, soluble iodide ion is easily oxidized to elemental (free) iodine that has low solubility in water and a high vapor pressure, thereby, increasing its volatility. However, the addition of antioxidants (e.g. sodium thiosulphate: $Na_2S_2O_3$) to either labelled or sodium iodine solutions of I-131 helps to reduce both decomposition and volatilization. The $Na_2S_2O_3$ solution helps to drive the reaction toward sodium iodide in solution, and to prevent the production of iodine gas [1, 8]. Therefore, in order to maintain the tracer in a stable solution form, thus preventing the release of tracer vapour (iodine gas), it was dissolved in 10 ml $Na_2S_2O_3$ of solution. This was further diluted into 1000 ml of water and instantaneously injected into the inlet slurry stream to the first tank through a pipe placed alongside the inlet feed pipe and at the same depth as shown in Fig. 3.

The distribution of tracer concentration with time at the outlet of the tank was determined by the on-line (*in-situ*) data collection method. This was achieved by installing a sodium iodide [NaI(Tl)] scintillation detector at the outlet of the tank to directly measure the ^{131}I concentration in the outlet slurry stream. Alongside this detector, was a second scintillation probe, completely shielded at the bottom with lead bricks, to measure background radiation. The detectors were driven by a data acquisition system (DAS) consisting of a LUDLUM model 4606 rate meter connected to a laptop computer. The signals (count rates) recorded by the detectors were transmitted through the cables to the rate meter and then stored on the computer for further processing. A picture summary of the on-line data collection including outlet detectors, rate meter and computer is shown in Fig. 3. The measured count rates were corrected for background and decay of the isotope (half-life = 192.96 h). The corrected data were then normalized and plotted against time to represent the RTD.

a Tracer injection point b Tank I outlet detectors c DAS

Fig. 3. Picture summary of *in-situ* data collection method.

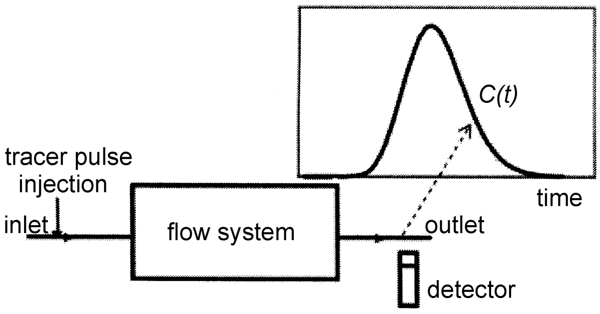

Fig. 4. Idea of RTD measurement.

RTD analysis and modelling

RTD concept

The RTD concept has been described in a multitude of scientific papers [2, 14]. The idea of its application to a flow system is shown in Fig. 4. The principle of a tracer experiment consists in a common impulse response method: injection of a tracer at the inlet of a system and recording the concentration time curve at the outlet $C(t)$. For the closed-closed system, that is the system with the internal mixing and plug flows (no mixing at all) at the inlet and the outlet, when the tracer is pulse injected, the RTD function $E(t)$ (or RTD) is obtained after normalization of $C(t)$. $E(t)$ is defined by the following equation [10, 14]:

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt} \tag{2}$$

RTD, as defined above, may be only applied to constant flow and constant volume systems. There are several physical parameters that can be obtained directly by experimental $E(t)$ function: mean residence time, mean velocity or flow rate, mixing intensity. It is also used for the diagnosis of reactor troubleshooting: parallel flows, stagnant zones or by-passes. More parameters of the flow kinetics can be extracted only through modelling the $E(t)$ curve.

Moments method

The method of moments is the fundamental method of estimating the distribution parameters. The $C(t)$ curve presents the quantity of a tracer flowing out of the system at a given time interval. The shape of $C(t)$ function is a result of velocity and stream line distributions, diffusive and turbulent exchange of matter or mechanical mixing. It is normalized to obtain the $E(t)$ function (Eq. (2)), which is equivalent to a probability density function, where the random variable is time t.

In this case the method of moments could be used for the analysis of experimental $E(t)$ curves and description of basic parameters for the behaviour of materials in a system.

The basic parameters in this case are:

$$\tau = \int_0^\infty tE(t)dt \tag{3}$$

$$\sigma^2 = \int_0^\infty (t-\tau)^2 E(t)dt \tag{4}$$

The first moment (Eq. (3)) of the experimental RTD gives the mean residence time τ of material inside the studied process. The second moment (Eq. (4)) estimates the dispersion σ which characterizes the spread of the distribution curve as a result of stream line distribution and turbulent or mechanical mixing intensity. Application of this method requires measuring full shape of the experimental $C(t)$ function. Stęgowski [25] has described the accuracy of calculating these parameters in detail.

Perfect mixer models

The perfect mixer (perfect mixing cells) is the basic flow model commonly used in modelling flow systems. It is broadly applied in flow studies of chemical engineering and environmental systems. The model is based on the assumption of instantaneous and uniform mixing of material in the whole volume of the system such that the concentrations of fluid within the systems and the outlet stream are the same. For the one perfect mixer model, the RTD function $E(t)$ has the following form [14]:

$$E(t) = (1/\tau)\cdot\exp(-t/\tau) \tag{5}$$

The perfect mixer is the basic model for building more complex models such as perfect mixing cells in series, mixing cells in series with backflow and mixing cells in series with exchange.

In the 'mixing cells with exchange' model each mixer of volume V_1 exchanges flow with another mixer of volume V_2 as shown in Fig. 5. In practice, this type of flow is commonly experienced in stirred vessels. From the mass balance of material flow through the mixers the model is described by the following equations:

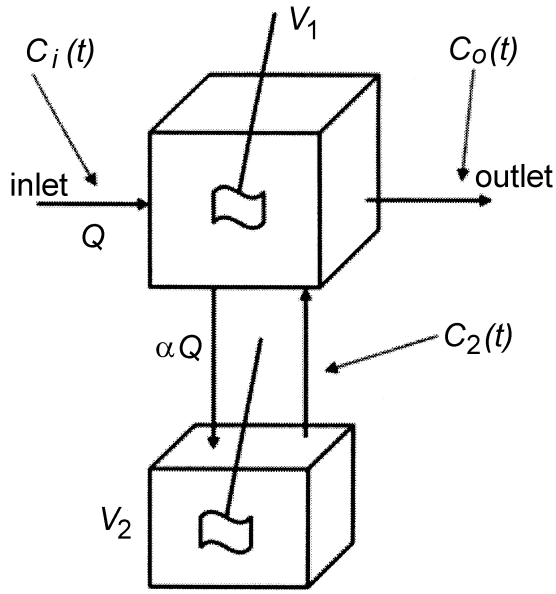

Fig. 5. Schematic diagram of mixing cells with exchange model.

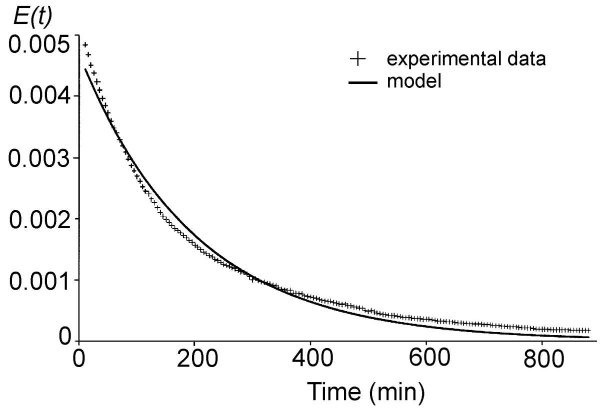

Fig. 6. Perfect mixer model fit of experimental data.

$$(6)\quad \begin{aligned} \frac{dC_o(t)}{dt} &= \frac{1}{\tau_1}\cdot\left[C_i(t)-(1+\alpha)C_o(t)-\alpha\ C_2(t)\right] \\ \frac{dC_2(t)}{dt} &= \frac{1}{\tau_2}\cdot\left[C_o(t)-C_2(t)\right] \end{aligned}$$

where $C_i(t)$, $C_o(t)$ are inlet and outlet tracer concentration functions of the main mixer respectively. $C_2(t)$ is the tracer concentration function in the exchange mixer, Q in Fig. 5 is a constant volumetric flow rate and α is the cross flow rate constant.

The model has three parameters τ_1, τ_2 and α. For this model, the total mean residence time τ is equal:

$$(7)\quad \tau = \tau_1 + \alpha\,\tau_2$$

The presented models can be combined in many ways to construct more complex models to suit the design of any system such as configurations involving series, parallel and recirculation flow [12].

Results and discussion

The residence time distribution curve representing the normalized tracer concentration vs. time is shown in Fig. 6 (dotted lines). The curve described a characteristic exponential decay typical of CSTRs. Usually, for a perfectly mixed system the count rate should return to zero after two or three mean residence times (MRTs) [12]. However, it was observed that the tail end of the data deviated from the ideality above though the experiment was carried out for about three mean residence times. The tail end of the data was, therefore, exponentially extrapolated to make it suitable for parameter estimation using the moment's method [25]. Two sets of points were chosen on the tail end of distribution curve for extrapolation. The first moment of the extrapolated data was in the range of 259 to 272 min with respects to the two sets of points used.

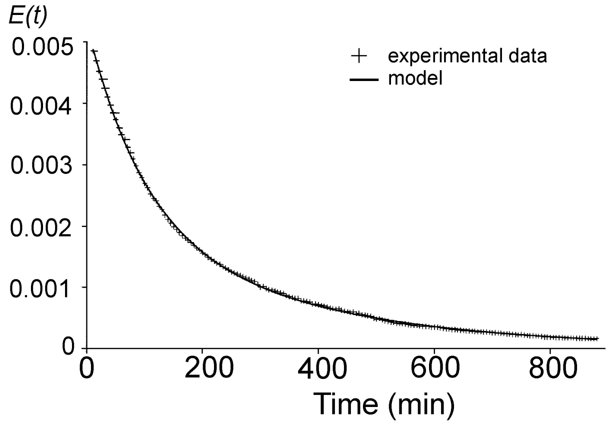

Fig. 7. Mixers with exchange model fit of experimental data.

The experimental RTD curve was fitted with ideal flow models typical of CSTRs in order to determine the most suitable model that describes the flow structure in the leaching tank. The shape of the experimental curve after normalization resembled a perfect mixer. However, as shown in Fig. 6, attempts to fit the data with the perfect mixer resulted in a significant deviation between the two. Initially, the exponential decrease of the data was faster than the model and *vice versa* at the end of the experiment. The tank was, therefore, not behaving as one perfect mixer. The method of tank agitation is such that mixing is more vigorous in the vicinity of the mixer than in other parts of the tank, such as around baffles and at the bottom of the tank. This type of tank design suggests the existence of multiple mixing zones in the tank [28]. Although other ideal model combinations that could fit this mixing method were used, the configuration that best fitted the data was the mixers with exchange model (Fig. 5). Modelling was performed by fitting the experimental RTD curve with the model's RTD function obtained from the numerical solution of its differential equations (Eq. (6)).

The mathematical calculations have been done to use the MATLAB software package to solve the equations numerically by "ODE45" function which uses the Runge-Kutta method. The model parameters were optimized by "FMINSEARCH" function. This function uses a derivative-free method to minimize the mean square error between the model end experimental data.

The model parameters are given in Table 1 and the RTD fit to the experimental data is shown in Fig. 7. Hence, the flow structure in the leaching process was such that there existed two mixing regions in the tank with the bulk material flowing through a well mixed zone of volume V_1 exchanging its contents in a cross flow manner with another mixing zone of volume V_2. In the flow line from the cyclones to the first CIL tank, there was no flow meter to directly measure the flow rate of

Table 1. Model parameters

Model	Model parameters						
	τ_1 (min)	τ_2 (min)	τ (min)	Q (m^3/min)	α	V_1 (m^3)	V_2 (m^3)
Two perfect mixers with exchange flow	198	149	265	11.3	0.45	2239	761

the inlet feed. The flow meter was rather installed between the ball mill and the cyclones. The flow indication of this meter does not represent the flow to the tanks because part of it is re-circulated to the ball mill. The average pulp flow rate from the cyclones to the tank was therefore determined from the model parameters and recorded in the table.

Conclusions

The hydrodynamic parameters of the first tank of the CIL section of Damang gold processing plant were investigated using radiotracer RTD method. The results showed that the behaviour of the tank was close to a perfect mixer though some deviations were observed in experimental and modelled data. The flow structure in the tank was best described by the mixing cells with exchange model in which two mixing zones existed in the tank. The volumes of the two zones determined from the model were 75 and 25% the nominal volume which could respectively correspond to regions of vigorous mixing and areas not in the vicinity of the mixer. Although short circuiting is a typical malfunction of CSTRs, it was not observed due probably to the design of the inlet into the tank. The feed was not allowed to flow directly into the tank but through a pipe buried a few meters from the surface. Finally, future investigations would be conducted to determine the total residence time of the whole CIL section using the identified model.

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