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Modelling of an autoclave used for high pressure sulphuric acid/oxygen leaching of first stage leach residue. Part 1: Model development

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ABSTRACT

Pressure leaching of the first stage leach residue in Base Metal Refinery (BMR) circuits aims to achieve high base metal dissolution with minimal precious metal leaching. Optimum autoclave operation is challenging because of the complex leaching chemistry, varying mineralogy of the feed material, and interaction between the different process variables. This research involved the modelling of the pressure leaching stages with flash recycle cooling at a typical BMR. The steady state solution employed the sequential modular approach in MATLAB, while the dynamic simulation involved the simultaneous solution of a set of differential equations, derived from mass and energy balances, in MATLAB. Part I of this communication presents a discussion of the Western Platinum Ltd. BMR process, an overview of relevant literature, and the strategies followed to develop both a steady state model and a dynamic model. Part II of this communication discusses the application of the models.

1. Introduction

1.1. Background

Platinum group metal producers typically employ a hydrometallurgical circuit, consisting of various stages of atmospheric and pressure leaching, for the treatment of nickel–copper matte to separate the base metals and platinum group metals. Lamya (2007) presented an overview of the hydrometallurgical circuits employed at Rustenburg Base Metal Refinery, Western Platinum Ltd. Base Metal Refinery, and Impala Base Metals Refinery, as well as the Outokumpu nickel–copper matte leaching process. Several laboratory scale studies have reported reaction rate constants for the reactions describing the sulphuric acid leaching of nickel sulphide and copper sulphide phases typically encountered in nickel–copper matte (Rademan, 1995; Provis et al., 2003; Lamya, 2007; Ruiz et al., 2007; Fan et al., 2010), while Dorfling et al. (2012) determined the leaching kinetics of the other precious metals (OPMs: rhodium, ruthenium, and iridium) and OPM phases during the high pressure sulphuric acid leaching of first stage residue.

Limited work has been done to incorporate the knowledge gathered from the kinetic studies into steady state or dynamic models of the nickel and copper leaching stages employed at Base Metal Refineries (BMRs). Faris et al. (1992) developed a computer simulation of a nickel–copper matte acid leaching process using SysCAD, with the focus being on the hardware and software used for the simulation rather than on the modelling of the fundamental concepts related to the process. The work did, however, illustrate how models could be used to assist with operator training, to evaluate the effects that variations in process variables have on the autoclave performance, and to evaluate different control strategies.

The objective of this study was to develop a model that would allow the prediction of the steady state behaviour of the pressure leaching stages at the Western Platinum Ltd. BMR, and to estimate the dynamic response of the leaching temperature and the leach solution composition (including the concentrations of the OPMs) to changes in the feed rates of the different components, the flow rate of the flash recycle stream, and the leaching pressure. This part of the communication focuses on the theoretical background, process description, and the model development. Part II of this communication discusses the application of the model to predict the system behaviour under various operating conditions.

1.2. Modelling of leaching reactors

The modelling of ideal, perfectly mixed reactors involves performing mass balances assuming that the temperature and the concentrations of all components are identical throughout the reactor and equal to the conditions in the reactor outlet. The overall mass balance approach is the simplest technique, neglecting the effect of particle size distribution and residence time distribution on the reactor performance. Although the modelling of reactions for which the rate depends on the available surface area might

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be less accurate if the particle size distribution of the feed is assumed to be monosized, it does allow easier calculations, is typically considered adequate for initial modelling studies (Nikkhah, 1998), and has been used in several leaching studies.

Lampinen et al. (2010) analysed the leaching of Zn concentrate in a non-ideally mixed continuously stirred tank reactor based on these simplifications. As discussed in Section 1.1, Faris et al. (1992) simulated the Sherritt nickel–copper matte acid leach process using the SysCAD software package. The sequential modular simulation approach was followed to solve the material balances as well as the dynamic flow sheets, and the Wegstein method (Felder and Rousseau, 2005) was used to perform the recycle convergence. Although no detail about the reactions and reaction kinetics was given, it was reported that simple rate expressions were used in an overall mass balance approach. Basic simplifications, for example estimating the density of a stream as the weighted average of the densities of the different components or assuming constant heat capacities over the specific temperature ranges, were in general acceptable to perform sufficiently accurate simulations of the leaching process to be used for control and operability studies, control system testing, and personnel training (Faris et al., 1992).

For reactors exhibiting non-ideal behaviour, knowledge about the residence time distribution, particle size distribution in the case of particulate reactors, and quality of mixing needs to be taken into account in the mass balances if highly accurate results are desirable. Fogler (1999) presented several models to estimate the performance of these types of reactors. For systems characterised by first order reactions, the residence time distribution can be used to predict conversions in the reactor. For systems characterised by reactions other than first order reactions, information regarding the degree of micro-mixing is also required (Fogler, 1999). The two extreme cases discussed by Fogler (1999) include complete segregation and complete micro-mixing, also referred to as "maximum mixedness". The segregation model will predict the highest conversion for reactions with reaction orders greater than one and complete micro-mixing model will predict the lowest conversion for these reactions, while identical performance will be predicted for first order or pseudo first order reactions. This is in agreement with the analysis of Crundwell (1994), who discussed the application of these models to particulate reactors in detail. This study furthermore illustrated that the two abovementioned models are identical if the leaching rates are zero order or pseudo zero order with respect to the concentration of the reagents in the liquid portion of the slurry.

In general, the differences between the performance predicted by the segregation model and that predicted by the maximum-mixed model will increase as the reaction order with respect to the reagent species in the liquid phase increases. Crundwell (1995) also referred to the three abovementioned methods (overall mass balances, population-balance models (considered to be the equivalent of the maximum mixed model), and segregated flow models) as the most commonly used methods for the modelling of leaching reactors. Both the segregated flow model (Papangelakis et al., 1990; Papangelakis and Demopoulos, 1992a, 1992b) and the population balance method (Papangelakis and Demopoulus, 1992b; Baldwin et al., 1995; Rubisov and Papangelakis, 2000) have been used in several studies to predict the performance of leaching reactors where non-ideal characteristics were to be accounted for. Crundwell (1995) considered the population balance method to be the most appropriate for the accurate modelling of leaching reactors.

Dixon (1996) discussed the limitations of both the segregated flow model and the population balance model for the modelling of leaching reactors. When applied to multistage leaching reactors on a tank-by-tank basis, the segregated flow model will not be appropriate if the leaching rate is not indicated by changes in particle sizes. The population balance method is considered more rigorous for the analysis of multistage leaching reactors, but is complex and difficult to apply. For the particular modelling method, the particle size distribution needs to be determined accurately, especially for the small particles. In addition, the derivation of the population balance model assumes perfect mixing in the reactor to which the model is applied. Dixon (1996) stated the above arguments as reasons why the population balance model has not been widely used for leaching reactor analysis, and presented an alternative method to the segregated flow model and population balance model to model the performance of leaching reactors. The proposed method, referred to as the multiple convolution integral, was claimed to address the deficiencies of the aforementioned techniques by mathematical manipulation of the leaching kinetics expressions to allow integration over residence time and particle size distributions. According to Crundwell (2005), however, the multiple convolution integral was simply a different formulation of the segregated flow model.

An alternative approach presented by Fogler (1999) involves modelling a real reactor by combining several ideal reactors. One of the examples presented illustrated how the performance of a stirred tank reactor with dead volume could be estimated using an ideal stirred tank reactor with a bypass stream. To evaluate the appropriateness of the selected combination of ideal reactors to represent the real system, extensive experimental data regarding the residence time distribution and particle size distribution of the solids feed stream are required.

For this study, the modelling of the autoclave was done by performing overall mass and energy balances without considering the particle size distribution of the feed or the residence time distribution of the autoclave.

2. Process overview

2.1. Process description

At the Western Platinum Ltd. BMR, the milled converter matte is sent to an atmospheric leaching stage (referred to as the first stage leach) where spent electrolyte from the copper electrowinning circuit is added. The copper in the electrolyte is precipitated during the leaching process, while approximately 70% of the nickel in the milled converter matte is dissolved. Lamya (2007) and Van Schalkwyk et al. (2011) presented detailed discussions of the operation of the first stage leach. The solid residue from the first stage leach is sent to the pressure leaching stages, which consist of the second stage leach (the first three compartments of the autoclave) and the third stage leach (the fourth compartment of the autoclave). The division of the autoclave into two stages allows improved control of residence time, temperature, and oxygen partial pressure during the final stages of leaching, which results in an increased concentrate grade (Steenekamp and Dunn, 1999). A schematic overview of the pressure leaching stages at the Western Platinum Ltd. BMR with the relevant unit operations and streams, as considered for the development of the process model, is presented in Fig. 1. All stream numbers referred to in this article refer to the corresponding stream in Fig. 1. The first stage leach residue (stream 1) is first sent to a slurry preparation tank where fresh water, acid, filtrate from the formic acid leach, and spent electrolyte are added. The formic acid leach is used downstream of the second and third leaching stages in order to further upgrade the solids residue from the pressure leach by dissolution of any remaining nickel and iron in the PGM concentrate. The filtrate from this leaching process is essentially a dilute sulphuric acid stream containing small amounts of iron and nickel; for modelling