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Real time optimization based on a serial hybrid model for gold cyanidation leaching process

Zhang Jun [a], Mao Zhi-zhong [a,b,*], Jia Run-da [a,b], He Da-kuo [a,b]

[a] School of Information Science & Engineering, Northeastern University, No. 3-11, Wenhua Road, Heping District, Shenyang, PR China
[b] State Key Laboratory of Integrated Automation for Process Industry, No. 3-11, Wenhua Road, Heping District, Shenyang, PR China

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ABSTRACT

To implement optimization and control on gold cyanidation leaching process (GCLP), it is an important prerequisite to establish an accurate process model. In this paper, a hybrid model in serial structure was proposed, where a first-principle model based on mass conservation equations was presented to describe the basic process behavior and its unknown kinetic reaction rates were predicted using BP ANN models without any structures considered. The proposed serial hybrid model had been applied to the prediction of gold recovery of the GCLP in a gold treatment plant. The results indicate that the proposed serial hybrid model has better prediction performance and generalization ability than the pure mechanistic model. To further reduce the effect of prediction error (plant-model mismatch) on real time optimization (RTO), modifier adaptation approach had been investigated and implemented to the GCLP. The result shows that when model mismatches with the actual plant or larger process disturbance occurs, significant reduction of production cost can be actualized iteratively by implementing the proposed adaptive RTO strategy.

1. Introduction

As the most important operation unit, leaching has been playing a significant role in hydrometallurgical process. Gold cyanidation leaching in aerated alkaline pulp has been the main process to extract gold from ores, concentrates and tailings for more than one century (Editorial committee of the gold production guide, 2000; Sun, 2008). In most of plants GCLP occurs in a cascade of continuous stirred tank reactors (CSTRs), which has the advantages of longer residence time, higher gold recovery, lower cost and wider adaptability to ore types (De Andrade Lima and Hodouin, 2005). As the most important procedure of hydrometallurgical process, the quality of leaching solution affects the subsequent procedures strongly. Gold recovery is the most significant production index and hence has an impact on overall gold production, production efficiency and so on. Usually the lowest production cost with the specified production efficiency or gold recovery satisfied is required in practice, which is achieved by applying appropriate optimization and control strategy to GCLP, i.e., determining the optimal set points of key control loops based on the given production target.

Prior to implementing optimization and control, it is necessary to establish an accurate process model. Recently, GCLP has been investigated widely. An electrochemical model based on kinetic model of gold ore cyanide leaching was formulated and fitted (Li et al., 1992; Rubisov et al., 1996; Wadsworth, 1991). An electrochemical mechanistic model based on the shrinking-particle model was presented by Crundwell and Godorr (1997), in which the mathematical model of leaching reactions was used to account for leaching electrochemical mechanisms, gold surface passivation and gold particle shrinkage. Wadsworth et al. (2000) proposed a mechanistic model in which the surface reactions were thought to control the gold dissolution rate kinetically. Afterward De Andrade Lima and Hodouin (2006) proposed a mechanistic model of GCLP that consisted of mass conservation equations of gold in the solid phase, gold in the liquid phase and cyanide in the liquid phase. Therein the kinetic models of gold dissolution and cyanide consumption were identified with a set of industrial data from an Australian plant. However, due to the complexity of kinetic reactions, the parameters and even structures of kinetic models are not the same as those above for plants with different production technology, raw material property, etc. Therefore the existing kinetic models usually result in poor model prediction performance for other plants. Hybrid modeling methods may be

* Corresponding author at: School of Information Science & Engineering, Northeastern University, No. 3-11, Wenhua Road, Heping District, Shenyang, PR China. Tel.: +86 13998240211; fax: +86 02423890912.

E-mail addresses: zhangjunroger@163.com (J. Zhang), maozhizhong@ise.neu.edu.cn (Z.-z. Mao).

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Nomenclature

a	gold recovery for the ith tank (%)
Ccn_i	cyanide concentration in the liquid for the ith tank (mg/kg)
Cl_i	gold concentration in the liquid for the ith tank (mg/kg)
Co_i	oxygen concentration in solution for the ith tank (mg/kg)
Cs_i	gold concentration in the ore for the ith tank (mg/kg)
Cs_∞	residual gold concentration in the ore (mg/kg)
Cw_i	solid concentration in the pulp for the ith tank (kg/kg)
$\bar{d}$	average size of the ore particles (μm)
Ml_i	liquid hold-up for the ith tank (kg)
Ms_i	ore hold-up for the ith tank (kg)
Qcn_i	cyanide flow rate added into the ith tank (mg/h)
Ql_i	liquid flow rate for the ith tank (kg/h)
Qs_i	ore flow rate for the ith tank (kg/h)
$r_{Au,i}$	dissolution rate of gold for the ith tank (mg/kg h)
$r_{cn,i}$	consumption rate of cyanide for the ith tank (mg/kg h)
t	time (h)
V_i	net volume of the ith reactor (m^3)

Greek symbols

ρs	ore density (g/cm^3)
ρl	liquid density (g/cm^3)
τ_i	average residence time for the ith tank (h)

Subscripts

i	number of the leaching tank

a suitable choice to improve model prediction accuracy. In our study, a serial hybrid model is proposed, where the mass conservation equations of gold and cyanide are used to describe the main process behavior and the two unknown kinetic reaction rates are estimated by BP ANN models. The above hybrid model not only makes full use of the available process knowledge but also has the advantage of easily discovering the relationship between two data sets by data-driven model (Gupta et al., 1999; Lee et al., 2005). Here, we only need to train the two kinetic reaction rate models (BP ANN models), which reduces the possibility to obtain a local minimum largely compared with identifying the whole model. Moreover, the serial hybrid model has better generalization performance (Bardow and Marquardt, 2004; Brendel et al., 2006). Furthermore, before training the above two models, we need to obtain effective and accurate estimates of the above two kinetic reaction rates due to the fact that the rates are unmeasurable or measuring them is costly in the actual plant. However, the rate estimation is an ill-posed inverse problem (Bakushinsky and Goncharsky, 1994) and the noise in concentration measurements is easy to be propagated into the rate estimates by derivative operation. Here, an effective estimation strategy based on the Tikhonov regularization method (Yeow et al., 2003) is proposed, which can reduce the effect of measurement noise on the estimates as much as possible.

Due to measurement noise, process disturbance and the limitation of production cost, it is difficult to obtain an accurate process model that matches with the actual plant absolutely. Therefore, the model-based optimization usually cannot provide an optimal operation for the actual plant, but only a suboptimal, or even infeasible one due to plant-model mismatch (uncertainty) (Mercangöz and Doyle, 2008; Yip and Marlin, 2004). A direct and effective method is to use the actual plant measurements to compensate for uncertainty iteratively, which results in measurement-based optimization (Darby et al., 2011). So far, no study associated with RTO of GCLP can be found in the open literature. RTO (real time optimization) is a typical and effective method to improve operating performance in process industries. As the most important level in the plant decision hierarchy structure, RTO serves as making medium-term (hours) production decisions in real time based on the economic objective, slowly changing conditions and nonlinear steady-state process model (Chachuat et al., 2009; Darby et al., 2011; Marchetti et al., 2009). The selection of the volumes of tanks in the cascade of leaching reactors was presented by De Andrade Lima and Hodouin (2005). The results showed that the plant performance could be improved by using a sequence of increasing size reactors for the same total volume. The effect of different network configurations for a gold leaching circuit with five equal-sized reactors was investigated by De Andrade Lima (2006). It was shown that the best configuration was not identical for different gold content and cyanide concentration. A systematic study of the optimal distribution of cyanide in a cascade of leaching tanks was performed by De Andrade Lima and Hodouin (2006). However, the above optimization problems are only the simulation studies based on a fixed mechanistic model, which are difficult to be applied in industrial practice. In this paper, an on-line adaptive RTO strategy of GCLP is proposed, where modifier adaptation approach is used to compensate for plant-model mismatch iteratively. When the process is confirmed to have achieved at a steady state by steady state detection procedure, the corresponding plant measurements are collected and preprocessed by gross error detection and data reconciliation procedures (Darby et al., 2011; Marlin and Hrymak, 1997). Then the preprocessed data are used to modify the corresponding terms in the measurement-based optimization problem. A better set point for the next iteration can be obtained by solving the modified optimization problem. Upon convergence, the proposed adaptive RTO strategy will theoretically converge to the optimal set point for the actual plant, yet usually a suboptimal but acceptable one due to the estimation errors of plant gradients in practice.

The paper is organized as follows: The proposed serial hybrid modeling method for GCLP is presented in Section 2, which consists of the description of the studied GCLP plant, the mechanistic modeling and then the serial hybrid modeling. In Section 3, a detail description of modifier adaptation approach is given. The practical applications of the proposed hybrid modeling method and the adaptive RTO strategy are shown in Section 4, which is composed of plant description and data collection, prediction with serial hybrid model and real time optimization on a gold plant. Conclusions are presented in Section 5.

2. Serial hybrid modeling

2.1. Process description

Extracting gold from ores typically consists of ore comminution, size classification, gravity concentration, pulp dewatering, gold leaching, gold recovery, gold elution, electrolytic extraction and finally melting and casting (De Andrade Lima and Hodouin, 2005; Sun, 2008). Of all the above procedures gold leaching is the most crucial. Gold leaching by cyanide solution in aerated alkaline pulp has been the main process of extracting gold. In order to improve its performance, the relevant researchers have investigated its chemistry widely (Crundwell and Godorr, 1997;