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A gradient optimization scheme for solution purification process

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ABSTRACT

This paper presents a two-layer control scheme to address the difficulties in the modeling and control of solution purification process. Two concepts are extracted from the characteristics of solution purification process: additive utilization efficiency (AUE) and impurity removal ratio (IRR). The idea of gradient optimization of solution purification process, which transforms the economical optimization problem of solution purification process into finding an optimal decline gradient of the impurity ion concentration along the reactors, is proposed. A robust adaptive controller is designed to track the optimized impurity ion concentration in the presence of process uncertainties, disturbance and saturation. Oxidation reduction potential (ORP), which is a significant parameter of solution purification process, is also used in the scheme. The ability of the gradient optimization scheme is illustrated with a simulated case study of a cobalt removal process.

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1. Introduction

Solution purification, which belongs to the more general area of separation science and technology, is a key step in hydrometallurgy (Flett, 1992). As a widely used approach to obtain pure metals from their raw ores, hydrometallurgy involves phase and status transforms of metal elements. Typically, a hydrometallurgy process is composed of leaching, purification and electrowinning. The raw ore is first treated in the leaching process, in which the valuable metal in the solid state ore is extracted and converted into soluble salts in liquid solution. As leaching process is not completely selective, pregnant leaching solution inevitably contains undesired impurity ions. The presence of these impurity ions would decrease the current efficiency in the subsequent electro-winning process in which pure metal is recovered, resulting in energy waste and downgrade of product quality (Bøckman & Østvold, 2000). Therefore, the pregnant leaching solution is required to be purified to a certain degree prior to final metal winning.

Owing to the heterogeneous property of raw ores, the types of impurity ions in the leaching solution are not unique. Consequently, a solution purification process is composed of several sub-steps designed to remove different impurities. For example,

solution purification of zinc hydrometallurgy consists of copper removal, cobalt removal and cadmium removal (Fig. 1). These impurity ions possess different physical and chemical properties. The technologies and reaction conditions adopted in the sub-steps are not the same. However, these different sub-steps do share some common features. The reactions conducted to remove different impurities are essentially oxidation reduction reactions and require the use of additive and in some occasions catalyst (Sun, Gui, Wu, Wang, & Yang, 2013).

The dosage of additive is crucial to both purification performance and production cost. An excessive amount of additive is a waste of costly material, while an insufficient amount fails to remove the impurity adequately (Kim, Kim, Park, Song, & Jung, 2007). However, due to the inherent complexity of purification reaction, fluctuation of previous leaching process, stochastic disturbance and interactions between the intermediate sub-steps inside purification process, it is difficult for the human operators to adjust additive dosage precisely in order to achieve economical and stable operation. As a consequence, some operators prefer to use an excessive amount of additive to achieve the required purification performance. More seriously, a large process fluctuation may even cause the failure to meet the desired purification degree.

The existence of these problems has attracted the attention of researchers from both metallurgy and control community. To the author's best knowledge, the study on solution purification process begins from 1871 (Bøckman & Østvold, 2000). After that, the research on solution purification process has passed through two

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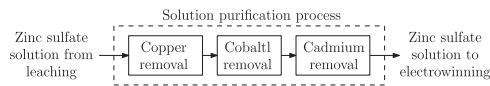


Fig. 1. Solution purification process in zinc hydrometallurgy.

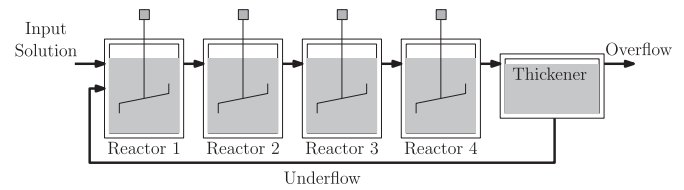


Fig. 2. Solution purification process.

stages of rapid development. The first stage of rapid development is driven by the mechanism study of solution purification process (Boyanov, Konareva, & Kolev, 2004; Bøckman & Østvold, 2000; Børve & Østvold, 1994; Dib & Makhloufi, 2007, 2006; Dreher, Nelson, Demopoulos, & Filippou, 2001; Fugleberg & Jarvinen, 1993; Lew, 1994; Nelson, Wang, Demopoulos, & Houlachi, 2000; Polcaro, Palmas, & Dernini, 1995; Sun et al., 2013; Tozawa, Nishimura, Akahori, & Malaga, 1992; van der Pas & Dreisinger, 1996; Yang, Xie, Zeng, Wang, & Li, 2006). It is found that the impurity removal reaction is first order solid-liquid phase kinetics/electrode reaction with its reaction rate affected by dosage and particle size of additive, temperature, pH and type of catalyst, etc. The second stage of rapid development is caused by the application of control theory to solution purification process which is usually conducted in CSTRs (Continuous Stirred Tank Reactors). Wu (2001) studied the use of a LMI (Linear Matrix Inequality) based robust model predictive controller to an industrial CSTR (Continuous Stirred Tank Reactor) problem with explicit input and output constraints. Knapp, Budman, and Broderick (2001) applied to a CSTR process an adaptive algorithm which uses a neural network representation to learn the process on-line. Antonelli and Astolfi (2003) studied the output feedback regulation of endothermic and exothermic chemical reactors in the presence of control bounds. Yu, Chang, and Yu (2007) proposed a stable self-turning PID (Proportional Integral Derivative) control scheme for multivariable nonlinear systems with unknown dynamics and applied the scheme to a simulated CSTR process. Di Ciccio, Bottini, Pepe, and Foscolo (2011) built a nonlinear feedback control law for a CSTR with recycle by using tools of differential geometry and observer theory. Hoang, Couenne, Jallut, and Le-Gorrec (2012) developed nonlinear control laws for isothermal CSTR based on the Lyapunov method. The above results mainly focus on the control of a single reactor. Wang, Gui, Teo, Loxton, and Yang (2012) and Li, Gui, Teo, Zhu, and Chai (2012) studied the use of control parametrization method to minimize the zinc dust consumption of a zinc sulphate electrolyte purification process composed of multiple reactors.

Different from the above research, this paper develops a control scheme for solution purification process based on its characteristics. The concepts of Additive Utilization Efficiency (AUE) and Impurity Removal Ratio (IRR) are proposed based on an analysis of solution purification process. By using these two concepts, the control of solution purification process is decomposed into two problems, i.e., estimated additive dosage optimization and robust adaptive tracking control of the optimized operating point. Correspondingly, the proposed control scheme is composed of two layers. The upper layer works on a slow time scale. The additive dosage optimization, which has an economic objective function subject to constraints on purification performance and process stability, is transformed into finding an optimal decline gradient of impurity ion concentration along the reactors. On contrast, the lower layer works on a fast time scale. A robust adaptive controller, in which Oxidation Reduction Potential (ORP) plays a central role, is designed to track the optimized impurity ion concentrations in the presence of model uncertainties, disturbance and saturation.

The rest of this paper is organized as following. In Section 2, an analysis of solution purification process is conducted. The problems arising in the control of solution purification are pointed out. The two-layer control scheme is introduced in detail in Section 3. The ability of the scheme is tested and discussed in Section 4. The concluding remarks are given in Section 5.

2. Process analysis

Solution purification process is a continuous process composed of N ($N \geq 1$, $N \in \mathbb{Z}$) consecutive reactors and a thickener in which the liquid–solid separation takes place (Fig. 2 shows a solution purification process composed of four reactors and a thickener).

Consider the reaction described by Eq. (1), along the reactors, impurity ion B is gradually reduced by reaction with additive A under specific reaction conditions and the assistance of catalyst. The overflow of the thickener is delivered to subsequent process. The underflow which contains crystal nucleus beneficial to impurity removal is recycled to promote cementation



The technical index and the economical index of solution purification process are the impurity ion concentration of the purified solution which reflects the purification performance, and additive consumption which relates to the production cost, respectively.

2.1. Process model

The reaction kinetics of Eq. (1) can be described by a first-order kinetic equation

$$\frac{dc}{dt} = -kA_s c \quad (2)$$

in which, c is the concentration of impurity ion, k is the reaction rate, A_s is the reaction surface area available for impurity removal in unit volume of the reactor.

Consider the process described in Fig. 2, assume that the fluid in each reactor is perfectly mixed, and the contents are uniform throughout the reactor volume. Then according to the mass balance principle, the dynamics of the process can be described by following equations:

$$\begin{aligned} \frac{dc_1}{dt} &= \frac{F_{in}}{V} c_0 - \frac{F_{in} + F_u}{V} c_1 - k_1 A_{s1} c_1 \\ \frac{dc_i}{dt} &= \frac{F_{in} + F_u}{V} c_{i-1} - \frac{F_{in} + F_u}{V} c_i - k_i A_{si} c_i \\ i &= 2, 3, 4 \end{aligned} \quad (3)$$

in which V is the volume of the reactor, F_{in} is the flow rate of the impure input solution from previous stage, F_u is the flow rate of the recycled underflow solution, c_0 is the impurity ion concentration of the input solution, c_j is the effluent impurity ion concentration of the j th reactor ($j = 1, 2, 3, 4$), k_j and A_{sj} are the reaction rate and reaction surface area in unit volume of the j th reactor ($j = 1, 2, 3, 4$), respectively.

2.2. Role of ORP

Purification process is essentially an oxidation–reduction reaction and also an electrode reaction composed of many parallel electrode reactions. According to the independence principle of parallel electrode reactions (Antropov & Beknazarov, 1972), the electrode reactions are independent of each other. Their unique shared characteristic is the electrode potential, which is also called

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