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Evaluation strategy for the control of the copper removal process based on oxidation–reduction potential

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HIGHLIGHTS

- A mechanistic model to estimate the relations between ORP and copper concentration is established.
- A fuzzy process evaluation method based on the mechanistic model is proposed.
- A control strategy for copper removal process is established integrated with the process evaluation method.
- The effectiveness of the proposed evaluation method and control strategy is confirmed through industrial experiments.

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ABSTRACT

The copper removal process purifies copper from leaching solutions with zinc powder in reactors. Due to the complex reaction mechanism and unavailability of online measurements, zinc powder is usually added inexactly, which easily leads to unstable production. This paper proposes an online evaluation method based on oxidation–reduction potential (ORP) for the control of the copper removal process. A kinetic model is designed to translate the production requirements to evaluation indexes of ORP, and the process is then graded by evaluating the fuzzified ORP and its trends according to these indexes. By analyzing these evaluation grades, the process condition is divided into several classes, and each condition class corresponds to a control method set. The industrial experiments show that the copper removal performance is improved by using the proposed evaluation and control strategy.

1. Introduction

Zinc hydrometallurgy is the main method of zinc production, producing more than 80% of the world's zinc [1]. This process is divided into five steps: roasting, calcine leaching, solution purification, electrowinning and melting [2]. The leached zinc sulfate solution contains various impurities (e.g. copper, cobalt, nickel, and cadmium) which lower the current efficiency and reduce the quality of the zinc ingot [3]. Therefore, the impurities need to be purified to an acceptable amount before electrowinning. Copper is commonly removed by zinc powder in the first stage of purification process because it has a more negative oxidation potential than the other impurities [4,5]. The purpose of copper removal process is to decrease the amount of copper ions in the leaching solution and reserve a portion of copper ions as activators used in the cobalt removal stage. Copper removal is usually carried out in a series of continuous stirred tank reactors (CSTRs), where ionic copper is deposited as metallic copper by adding zinc powder ($CuSO_4 + Zn \rightarrow ZnSO_4 + Cu$). In some improved processes, a portion of the deposited metallic copper is returned to the first reactor, where the ionic copper goes on to react with metallic copper and is precipitated as cuprous oxide ($Cu + CuSO_4 + H_2O \rightarrow Cu_2O + H_2SO_4$) [6].

These two reactions are mutually competitive as they consume the same reactant, and the former reaction can promote the latter one because the product of one reaction is the reactant of the other. Due to the interactions between the reactions, the copper removal process is sensitive to the reaction conditions [7]. Meanwhile, real-time concentration measurements are unavailable in the copper removal process because on-line element analyzers are costly, require complex maintenance, and are of questionable reliability [8]. In addition, the variations in the removal reactions are incapable of being determined. Accordingly, excess or insufficient amounts of zinc powder are usually added, making the entire purification process unstable.

Recently, many researchers have considered oxidation reduction potential (ORP) for monitoring and controlling the industrial

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chemical process [9–11]. ORP reflects the extent of the oxidation–reduction reaction and provides insight into the state of the reaction system that other parameters cannot reveal. Additionally, ORP sensors are low-cost, available online, and industrially feasible [12]. Due to these advantages, ORP has been applied in the monitoring and control systems of many biological and chemical processes such as biological nitrogen removal, wastewater treatment, and uranium extraction [13–15]. Ruano et al. applied fuzzy logic in the control of the biological nutrient removal process using ORP and pH sensors [16]. In the control method, the ORP and pH values are fuzzified, and the amounts of the control variables are then adjusted based on the fuzzy controllers using the fuzzified ORP and pH values are the inputs. Yu et al. presented the ORP potential as one of the key parameters to control the E-Fenton process for wastewater treatment by applying artificial neural network [17]. Won and Ra used moving slope changes of ORP to identify the condition of real-time control points for the aerobic and anoxic phases in the wastewater process [18]. These applications show that ORP has great potential for the industrial chemical processes control and provide useful advice for applying ORP in the copper removal process.

Notably, in the studies mentioned above, the impact of ORP on the control variables should be determined exactly before monitoring and controlling these processes. Sun et al. built a mathematical model by applying the electrode reaction kinetics to determine the relationships between ORP and the reaction rate in the cobalt removal process of zinc purification [19]. The model was applied to predict the cobalt concentration of the outlet purified solution, which offers an effective way to model the copper removal process with ORP in this paper. However, this method cannot be applied directly in the studied process because the copper removal occurs in the upstream stage of the cobalt removal. The contents of the impurities in the copper removal stage are considerably higher than those in the cobalt removal stage. Each of these impurities, which are mostly unavailable, influences ORP. Consequently, ORP is able to roughly estimate the copper removal reaction state, whereas it can hardly estimate the reaction rate exactly.

Fuzzy logic offers an effective solution to solve this problem with inherent difficulty and uncertainty [20,21]. It can transform uncertain information and human linguistic data into mathematical formulas and vice versa, and it is also easily understood and developed. Due to these advantages, fuzzy logic has been widely applied in the control of industrial processes [22–25]. It has been introduced for solving uncertainty problems in the detection of multiple combined faults on the online assessment of faulty conditions in an induction motor [26,27]. It has also been applied to construct fuzzy logic controllers when the mathematical models of the controlled objects are undefined or uncertain [28,29]. Considering these advantages, we introduce the fuzzy logic technique to evaluate the copper removal process for solving the uncertainty problem in the kinetic model based on ORP. The amount of zinc powder could then be determined in real time according to the evaluation results. Therefore, the objectives of this work are as follows: (1) to build a kinetic model for obtain quantitative acceptable ranges of ORP with the impurity concentration limits; (2) to propose a fuzzy evaluation method, based on ORP and its acceptable ranges, for the copper removal process; and (3) to implement a control strategy integrating with the evaluation method, thereby improving the quality of the outlet copper concentration and stabilizing the production process.

2. Materials and methods

2.1. Pilot plant and monitoring system description

The evaluation and control strategy was developed and tested in a zinc hydrometallurgy plant of China. The flow chart of the copper removal process in the plant is shown in Fig. 1. Zinc sulfate solution fed into copper removal is pumped from the leaching process. The solution consists of various impurities among which the content of copper is highest. Copper ions are removed in two full-filled connected continuous stirred tank reactors (100 m^3). The amounts of zinc powder are added by weight belts. Most of the copper ions are deposited in the first reactor by the bulk of the zinc powder, while a small amount of zinc powder is fed into the last reactor to maintain the outlet copper concentration within the desired range. After the precipitation reaction is finished (approximately 50 min), the purified solution is sent to a thickener to separate the clean solution and the precipitate. The clean solution from the top of the thickener is pumped to the next impurity removal stage, and the part of the precipitate from the bottom of the thickener is returned to the first reactor. The remaining precipitate is sent to the copper recovery process.

A series of sensors are installed in the copper removal process to obtain on-line information about the process state. These sensors are connected to a network system that includes several analog–digital converters (ADC), transmitters, a programmable logic controller (PLC), and an industrial computer. Most of the process parameters (e.g. temperature, pH, ORP, etc.) are monitored online every minute. The impurity concentrations in the inlet and outlet solutions are measured manually every two hours. The amounts

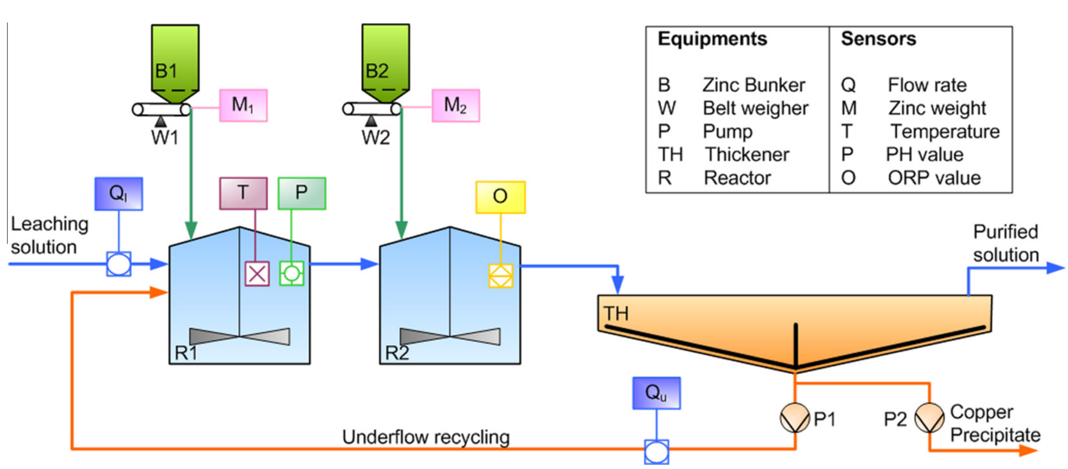

Fig. 1. Flow diagram of copper removal in the zinc purification process.