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Intelligent optimal setting control of a cobalt removal process

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ABSTRACT

Cobalt removal process is an important step in zinc hydrometallurgy. Because of its complex reaction mechanism and dynamic characteristics, human supervision with low level control is not sufficient to keep the stable and optimal operation of cobalt removal process. This paper presents an intelligent optimal setting control strategy of cobalt removal process. The control strategy consists of process monitoring unit, zinc dust utilization factor (ZDUF) estimation unit, cobalt removal ratio (CRR) optimal setting unit, oxidation reduction potential (ORP) setting unit and case based reasoning (CBR) controller. Process monitoring unit judges the state of current process. When process is at steady state, economical optimization is conducted by allocating suitable CRR to reactors according to their ZDUF. In order to realize automatic control, CRR is transformed into the setting value of ORP through an integrated model which is also able to estimate outlet cobalt ion concentration. When a process is at an abnormal state, case based reasoning controller is triggered to handle the undesired situation by providing rational solution of control variables. An industrial experiment shows that by using the proposed control strategy, zinc dust consumption can be reduced while the required cobalt removal performance is always achieved. Stability of cobalt removal can also be improved by limiting CRR of each reactor in predefined ranges.

1. Introduction

Zinc hydrometallurgy is the main method in zinc production. Currently, more than 80% of the world's zinc metal output is produced using zinc hydrometallurgy technique, which is composed of roasting-leaching-electrowinning or direct leaching-electrowinning [4,22]. However, because of the impurity of zinc ore, zinc sulfate solution after leaching inevitably contains other metallic ions, such as copper, cobalt, nickel and cadmium. The existing of these impurity metal ions would cause large drops of current efficiency in electrowinning from which metallic zinc is recovered. It will also cause the zinc to stick to the cathodes and spoil zinc cathode quality, resulting in energy waste and downgrade in product quality. Therefore, these impurity metal ions need to be purified to allowable content before electrowinning.

Among the impurities, cobalt ion is of particular concern, because even low levels are harmful and it is extremely difficult to remove because of high kinetic barriers [29]. Usually cobalt removal is conducted in three to five consecutive reactors by adding zinc dust and arsenic/antimony trioxide. High temperature is also supplied to provide enough reaction impetus. The technical indicator and economical indicator of cobalt removal process are effluent cobalt ion concentration which reflects the purification performance, and zinc dust consumption which relates to production cost, respectively. The task of human operator is to achieve and maintain the required effluent cobalt ion concentration by adjusting setting values of control variables according to the variation tendency of monitoring variables. This kind of operation mode based on human experience can obtain desired purification performance in most of the cases. However, the inherent complex dynamics of cobalt removal process give rise to the nonlinearities and strong couplings between the technical indicator and control variables. In addition, in some plants, due to its hostile environment and the high cost of purchasing online determination equipment, cobalt ion concentration is determined by time consuming chemical assay. So it is difficult for human operators who has limited understanding and information of current process to perform an optimal operation. Sometimes the variation of upstream process and zinc ore content [13] even cause the failure to meet the requirement of effluent cobalt ion concentration.

Because of the difficulty in its modeling and control, cobalt removal has been an important topic industrially and in academia for many years [5]. Researchers from metallurgy and process control community have done continuous effort on its kinetic research and controller design, such as investigation of suitable reaction

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condition by analyzing the influence factors and their influence mechanism [29,6], determination of the reaction type [31], reaction kinetic study by analyzing reaction products using scanning electron microscope (SEM) or energy-dispersive X-ray spectroscopy (EDX) [5], statistical analysis [27], process monitoring [28] and optimal control using control parameterization method [24,37]. Their research has revealed many aspects of cobalt removal process. However, there still lack process model capable of detecting cobalt ion concentration online. The proposed optimal control method also stays at simulation stage.

These problems arising in cobalt removal process commonly exist in process industry. In the last fifty years, many approaches have been proposed and applied to process control, such as PID control [3], expert control [2], fuzzy control [18], model predictive control (MPC) [33], cased based reasoning (CBR) [10], intelligent integrated control [39], simultaneous dynamic optimization [15], real-time optimization (RTO) [11,40], approximate dynamic programming (ADP) [23,14], and statistical process control (SPC) [26], etc. These approaches have been proved to be useful. However, because of the diversity of metallurgy processes, the development of a general optimal control method for the usual process in the metallurgic industry is still unrealistic [7]. For a particular process, the realization of control objectives relies on the design of control strategy and selection of control method based on the understanding of its nature and characteristics. An intelligent switch control strategy was proposed for the pulverizing system of an alumina sintering process. It is consisted of a coordinating controller, a proportional-integral (PI) controller, a rule-based reasoning controller and a switching mechanism [8]. A two level control strategy was used in industrial copper solvent extraction process. The stabilizing layer regulates the flow rates in the copper solvent extraction process [19]. The optimization layer maximizes the production of the copper solvent extraction process and gives set-points to the controllers at the stabilizing level. An optimal power-dispatching system was developed to minimize the cost of power consumption in the electrochemical process of zinc [41]. A back-propagation neural network (BPNN) was used to describe the relationship between main factors and power consumption. The constrained optimal problem was solved by using a equivalent Hopfield neural network. Total electrical energy consumption was reduced obviously after installation of the optimal power-dispatching system.

Specifically, cobalt removal process is a gradually decline process of cobalt ion concentration. The amount of zinc dust dosage depends on the estimation of its efficiency in removing the impurity [17]. According to mass balance, the efficiency varies with reaction rate. Thus zinc dust efficiency is time varying and different among the reactors. If different cobalt removal task plans are allocated to reactors, the total zinc dust consumption will be different. There exist a most economical allocation of cobalt removal task, in other words, an optimal decline curve of cobalt ion concentration.

Based on this idea, an optimal control frame was constructed using two concepts: ZDUF (zinc dust utilization factor) and CRR (cobalt removal ratio). The control frame consists of process monitoring unit, ZDUF estimation unit, CRR optimal setting unit, oxidation reduction potential (ORP) setting unit and case based reasoning (CBR) controller. Process monitoring unit was used to judge the state of current process. When process was at steady state, optimal CRR was obtained according to ZDUF of each reactor at each optimization step. Stability of cobalt removal process was also achieved by limiting CRR of each reactor in predefined ranges. The optimal CRR of each reactor were transformed into the values of control variable ORP through an integrated process model. By this way steady state optimization was approached. The integrated model is also able to estimate outlet cobalt ion concentration of each reactor. When cobalt removal process was at abnormal state, regulation of process state would be more significant compared with economical optimization. So a CBR controller was triggered to provide rational setting values of control variables [45]. An industry experiment in a zinc hydrometallurgy plant shows the improvement in zinc dust consumption and process stability by applying this optimal control frame.

2. Process description and control problem analysis

Cobalt removal is an intermediary step of the solution purification process in zinc hydrometallurgy (Fig. 1). It is a continuous process composed of consecutive continuous stirred tank reactors and a thickener (Fig. 2). In cobalt removal process, zinc dust and arsenic trioxide is added into reactor to conduct complex chemical and electrochemical reactions with cobalt ions and remaining copper ions of previous copper removal process. Spent acid is also supplied to provide an acidic reaction environment. By forming metal compounds, such as cobalt–arsenic and cobalt–copper, cobalt ions is gradually precipitated ((1)–(4)). After retention in consecutive reactors, zinc sulfate solution flows into the thickener in which liquid–solid separation takes place. Overflow of the thickener is delivered to subsequent cadmium removal process, while the underflow which contains crystal nucleus beneficial to cobalt removal is recycled to promote cobalt cementation.

$$\mathrm{Cu^{2+} + Zn = Zn^{2+} + Cu} \tag{1}$$

$$\mathrm{As^{3+} + 3Cu^{2+} + 4.5Zn = Cu_3As + 4.5Zn^{2+}} \tag{2}$$

$$\mathrm{As^{3+} + Co^{2+} + 2.5Zn = CoAs + 2.5Zn^{2+}} \tag{3}$$

$$\mathrm{As^{3+} + Ni^{2+} + 2.5Zn = NiAs + 2.5Zn^{2+}} \tag{4}$$

$$\mathrm{2H^{+} + Zn = Zn^{2+} + H_2} \tag{5}$$

Realization of required purification effect, economical optimization and process stabilization are three main control objectives of cobalt removal process. As cobalt ion concentration can not always be measured online, human operators usually control cobalt removal process by adjusting setting values of control variables according to the variation trend of online monitoring variables, such as flux of zinc sulfate solution, underflow and spent acid, dosage of zinc dust and arsenic trioxide, temperature and ORP. By try and trial, human operators accumulated certain amount of experience. When process is at steady state, their experience is sufficient to handle the setting of control variables to achieve required effluent cobalt ion concentration. However, cobalt removal is a complex multiphase reaction influenced by numerous factors, such as temperature, pH, dosage of zinc dust and arsenic trioxide, grain size of zinc dust, concentration of cobalt ion and copper ion, etc. The relationship between effluent cobalt ion concentration, control variables and online monitoring variables is very complicated involving nonlinearities and strong couplings. Decision based on experience cannot always provide optimal setting values of control variables. Moreover, zinc ore contains intricately mixed minerals with randomly varying properties, especially in metallurgy plants of China whose ore is purchased from different mines. Hence, large fluctuation of process happens occasionally.

Among all the control variables, zinc dust dosage is of great importance. An excessive amount of additive is a waste of costly material, while an insufficient amount fails to remove the impurity adequately. According to mass balance principle, the amount of zinc dust to be fed into the reactor depends on its efficiency in removing the impurity [17]. If we assume the fluid in each reactor is perfectly mixed, the contents are uniform throughout the reactor volume. Therefore, the steady state mass balance equation of cobalt ion in a single reactor can be expressed as:

$$V\frac{dc}{dt} = Fc_{in} - Fc - Vr_c \tag{6}$$