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Optimal control strategy of working condition transition for copper flash smelting process

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ABSTRACT

Because there are large state fluctuation of working conditions, excessive energy consumption caused by manual operation in the dynamic transient procedure for copper flash smelting process. Working conditions of copper flash smelting process must be adjusted to the complex and variable copper concentrate feeding to satisfy the smelting performance. Optimal control strategy based adjustment cost for copper flash smelting working condition transition is proposed, which can achieve the expected working condition by following the optimal working condition transition path. The Cauchy–Schwarz inequality-based two-level matching method is developed to set the expected working condition. Then with minimizing adjustment cost and restricting operation domain to optimize smelting performance indicators, the optimal control problem of working condition transition is converted into a multi-constraints optimization problem with two fixed ends. A Legendre pseudospectral-based optimization method is also presented to obtain the path of optimal working condition transition. The simulation results of actual production data collected are given to verify the effectiveness and feasibility of the proposed strategy.

1. Introduction

As a main production method employed for extracting copper from its sulphide ore, the copper flash smelting process is widely used throughout the world, which accounts for about 50% of global capacity for primary copper production (Najdenov, Raić & Kokeza, 2012). The complexity and variety of the copper flash smelting process is inherently aroused by the diversity of copper concentrate feeding usually includes different compositions of Cu, Fe, S, SiO_2, etc., as the ore comes from different mines. As a result, the key process indicators (matte temperature, matte grade and mass ratio of Fe/SiO_2 in slag) cannot be maintained within desired range. The control of key process indicators requires real-time information of concentrate feeding composition and key process indicators to set the operational parameters including the amount of O_2, air and SiO_2. If the concentrate feeding changes, the working condition will be migrated from current state to an expected one in order to guarantee smelting performance, which is known as working condition transition. Currently, the working transition mainly be realized by adjusting operational parameters step-by-step based on subjective experiences, which may not be stable and the transition time is usually very long. The smelting performance may also not be guaranteed, which can significantly influence the product quality and waste significant copper concentrate resources and power energy (Gui, Yang, Chen & Wang, 2013). Hence an optimal control strategy of working condition transition for the copper flash smelting process is urgent to reduce energy consumption and stabilize smelting product quality. It can be also important to improve the energy efficiency of a smelter (Saramak, Tumidajski & Skorupska, 2010).

Recently, considerable attentions have been devoted to optimize the operational parameters with genetic algorithm (Wang, Zhang, Zeng, Tong & Zhang, 2008), genetic particle swarm algorithm (Peng, Gui, Huang, Hu & Li, 2008). The method of fuzzy neural networks is also proposed to optimize the operation of copper flash smelting process (Peng, Gui, Li, Hu & Wang, 2007). However, most of the existing methods are only useful for setting the optimal operational parameters other than optimizing the dynamic adjustment procedure form current status to the optimal one. Moreover, the existing optimization methods requires the real-time key process indicators information (Gui, Wang, Yang, Xie & Peng, 2007; Koskinen & Torvela, 1989), which is yet difficult to obtained due to the complex reaction mechanism and poor smelting environment.

This paper not only focuses on the smelting performance of copper flash smelting process, but also pays more attention on the optimization method of dynamic transition procedure. The executive consumption of time and resources/energy is reduced, and

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the drastic fluctuation during the transition procedure is restrained. An adjustment cost oriented optimal control strategy of copper flash smelting working condition transition is proposed. Firstly, the optimization strategy of working condition transition of copper flash smelting is divided into two sub-strategies: one is to set the expected working condition according to the copper concentrate feed, and another is to optimize the working condition transition path from the current working condition to the expected one. The main contributions can be devoted to the following: (i) a Cauchy–Schwarz inequality-based two-level fast matching method is proposed to quickly retrieve the expected working condition from the history database with two matching processes; (ii) in terms of the transition time and energy consumption, an adjustment cost evaluation function is proposed to evaluate the copper flash smelting working condition transition performance. The path selection problem of copper flash smelting working condition transition can be converted into an optimal control problem which is subject to multi-constraints and fixed ends; and (iii) a Legendre pseudospectral-based method is proposed to optimize the working condition transition path. Finally, simulation results of actual running data collected from a copper flash smelting process are given to verify the proposed strategy.

The rest of this paper is organized as follows. In Section 2, the working condition transition for a copper flash smelting process is described. The framework for achieving the expected working condition by matching methods is given in Section 3. The adjustment cost is proposed to evaluate the copper flash smelting working condition transition performance by considering the transition time and transition energy consumption. The optimization strategy of copper flash smelting working condition transition problem is solved in Section 4. In Section 5, our proposed method is implemented based real production data collected from a copper flash smelting process. Finally, conclusions and future works are given in Section 6.

2. Description working condition transition of copper flash smelting process

2.1. Copper flash smelting process

The copper flash furnace is the main pyrometallurgical equipment for smelting copper sulphide concentrates. Fig. 1 shows a scale structure of flash furnace composed of reaction shaft, sedimentation tank and gas offtake (Chen et al., 2004).

In the flash smelting process, the dried copper concentrate and air, preheated oxygen enriched air or pure oxygen blast are fed through a concentrate burner into the flash furnace reaction shaft. Owing to the particular smelting reaction environment, the oxidation reaction of copper sulfide concentrate can be carried out flash, and a large amount of reaction heat are generated simultaneously in the flash furnace, which makes the copper sulfide

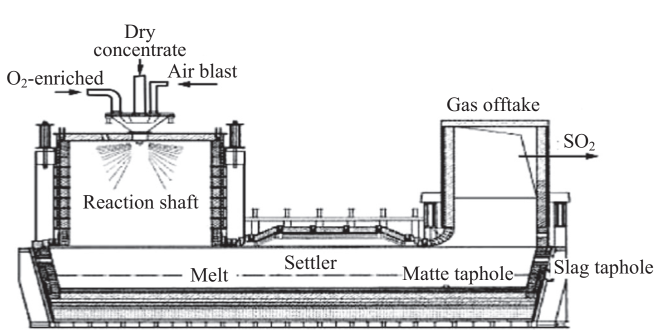

Fig. 1. The scale structure of flash furnace.

concentrate can be reacted through self-heating. In the reaction shaft, the temperature and gas composition distributions as well as the particle dispersion and residence time are difficult to be exactly described especially during the transition of working condition. For simplicity, the main parameters and data information are collected from a Smelter with average statistics. The following main oxidation reactions take place in the reaction shaft:

$$CuFeS_2 + \frac{5}{4}O_2 = \frac{1}{2}(Cu_2S{\cdot}FeS) + \frac{1}{2}FeO + SO_2 \tag{1}$$

$$FeS_2 + O_2 = FeS + SO_2 \tag{2}$$

$$FeS + \frac{3}{2}O_2 = FeO + SO_2 \tag{3}$$

Due to the quickness of copper sulfide particle reacted, some part of FeS are oxidized to FeO, even to the Fe_3O_4. But the Fe_3O_4 will be decomposed into a magnetic iron oxide under the existing environment of SiO_2

$$3Fe_3O_4 + FeS + 5SiO_2 = 5(2FeO{\cdot}SiO_2) + SO_2 \tag{4}$$

Cu_2S and FeS form the heavier matte phase, while the oxide comprise (such as FeO, Fe_3O_4, SiO_2 and a few Cu) form the lighter slag phase. SO_2 leaves with off gas along with combustion products, water and inert such as nitrogen. Then matte and slag will be detached at the settler of the flash furnace in different layers due to different density. The matte is tapped out through the matte tadpole located at the side or the end walls of the settler, and then fed to the downstream converter by a matte stream tank. The slag will be discarded after being recycled in the depleted furnace (Jämsä-Jounela, Vermasvuori, Endén & Haavisto, 2003). The practical experiences show that, the matte temperature, matte grade and the mass ratio of Fe/SiO_2 in slag are the key product indicators to evaluate the copper flash smelting performance. Once the key process indicators are stabilized in the smelting process, the stability of the downstream processes (such as blowing and sulfuric acid) can be guaranteed (Parada, Parra & Wilkomirsky, 2004). The key product indicators are mainly influenced by the copper concentrate feeding flux, the composition of Cu, Fe, S and SiO_2 in copper concentrate, and the operational parameters (Ronan, Pritzker & Budman, 1997).

The reaction in the copper flash smelting process is to comply with the law of conservation of mass/energy. In this paper, we assume that minor species such as PbS and ZnS in the matte and Cu_2O, PbO, ZnO, CaO, and Al_2O_3 are not considered, and the SiO_2, N_2 and H_2O are chemically inert. In fact, several works have been described change process of major species and temperature by using mass/energy balances method (Liu et al., 2012; Higgins, Gray & Davidson, 2009; GUI et al., 2007). Based on desulfurization ratio of copper concentrate, the developed model (Liu, Gui, Xie & Yang, 2014) couples dynamic mass balances on each species with equilibrium relationships for major component (Cu, Fe, S, SiO_2, et al.) to form a system of differential and algebraic equations, which verify the effectiveness. Given these factors, if the feed composition is variable in mineralogy, some proportion of the main components will be enough to determine the manipulated variable values to reach the desired final state.

2.2. Problem analysis

2.2.1. Problem formulation of working condition transition

In order to ensure the smelting product quality, a proper balance relationship among every composition should be met. When the copper concentrate resource change, the operational parameters should be adjusted to achieve the excellent smelting