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Research on Mathematical Model of Oxygen Content in Bell Furnace Based on Industrial Data

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A model of the oxygen content in the bell furnace is obtained by taking the furnace leakage flow into consideration based on the method of mechanism modelling. On the basis of mass conservation law, the relationship between the oxygen content in the bell furnace and the pipeline flow are presented while the leakage of the bell furnace and its effect on oxygen content is deduced according to Bernoulli's equation. Secondly, the oxygen content process model of the bell furnace is appropriately simplified to obtain the system transfer function, and the effect of the time delay is considered to modify the transfer function of the process model. The experiment is then applied to a real bell furnace, the step response and a typical craft response are measured and compared with the simulation. In the typical craft response experiment, the average error between the simulation and the experiment is 2.1819 mV measured in voltage when the oxygen content is above 0.01 %. The results indicate that the process transfer function based on first principle modeling is significant when the oxygen content is above 0.01 %, and can be further applied in designing oxygen control method both in close loop and open-loop control system.

1. Introduction

The bell furnace is important equipment for magnetic materials sintering while the production process of magnetic materials requires the sintering equipment to form a nitrogen protection atmosphere. It is one of the electric heating furnace, and uses resistance to heat magnetic materials. The temperature and the oxygen content in the bell furnace need to be controlled under a specific logarithmic relationship according to the Blank equation (Huang et al., 2014). In order to control the oxygen content, the open-loop control method is widely used not only for the unknown of the oxygen content process model but also for the inefficiency of tuning PID(Proportion Integration Differential) parameters in close-loop control. Other oxygen content control methods are researched in recent years, but many of them are based on fuzzy logic control, neural network or other non-model based methods.

The mathematical model is applied to describe the essential characteristics of a physical or chemical process. It is an important tool to theoretically explore the regular pattern of a process, which also leads the optimization of control methods (Ding, 2014). There have been many studies of the mathematical model in various fields, for example, the fast pyrolysis plant of lignocellulosic biomass (Jaroenkhasemmeesuk et al., 2020), the VOC removal silo (Egedy et al., 2019), the burden distribution in the blast furnace (Mitra et al., 2016). Molina et al. (2010) presented a full detailed model of the MHPP and a new three-level control scheme which is much simpler and lower cost of the power plant. Cadini et al. (2016) described an extreme weather stochastic model which can be applied to quantify the impact of extreme weather events on the reliability/availability performances of the power grid. Zhang et al. (2015) investigated a dynamic mathematical model of the molten salt cavity receiver which can be further used in system simulations of entire power plants. Belkassmi et al. (2018) developed the solar cell model with only one exponential. Many studies have proved that the correct understanding of process model is significant, but seldom can be applied directly in the bell furnace's oxygen process model. Some non-model based oxygen control methods may result in the overshoot and slow convergence in close loop control, or large rise time and steady-state error in open loop oxygen control. Those defects will deteriorate the product's

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inductance. This paper aims to propose the oxygen process model of bell furnace which can be used and referred in further research about oxygen content control.

There are generally two ways to obtain models. The first one is based on the laws of physics or chemistry which is called mechanism modeling or first principle modeling (Li, 2018). However, this method is not proper for complex process system for its high non-linearity and strong coupling among variables. The other is based on the least square method with the collected input and output data. In recent years, the identification method based on neural networks has also been widely researched (Li et al., 2019). The mechanism modeling requires a lot of assumptions, which may easily result in impracticability in actual industrial cases. This paper uses the data from industry to verify the correctness of the proposed model and can be the theoretical basis for subsequent controlling method.

In this paper, a model of the oxygen content in the bell furnace is studied. The pattern of oxygen content is derived through the mass conservation law while the flow of the gas at the leakage is taken into consideration. Then this process model is simplified. Both the step response experiment and a typical oxygen open-loop control experiment are implemented on a bell furnace. And the results of experiments and simulations from MATLAB are also compared and analysed.

2. Process model of the bell furnace

The oxygen content control system of the bell furnace is shown in Figure 1. Two mass flow controllers(MFC) are used to separately regulate the flow of air and nitrogen. The opening of electric butterfly valve is controlled by a PID(Proportion Integration Differentiation) controller, so that the extraction flow is regulated to maintain a stable pressure at the preset value which is usually set as a constant when the equipment is running.

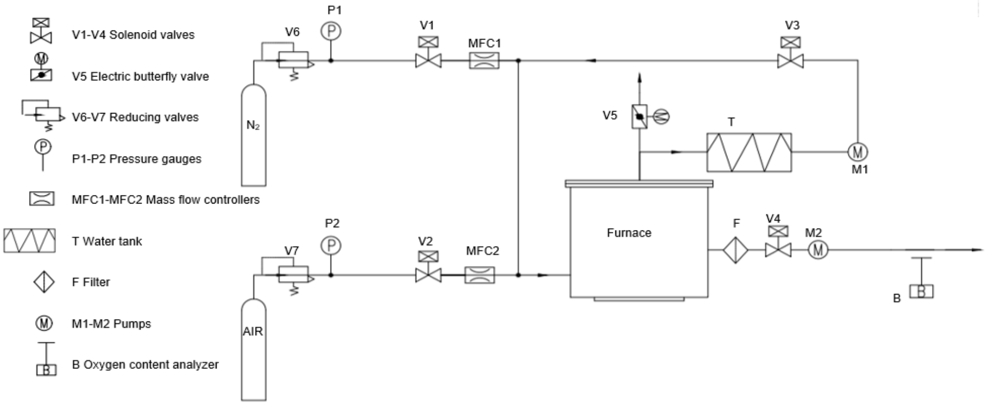

Figure 1: Oxygen content control system of the bell furnace

The flow of nitrogen is denoted as Q_N, and flow of air as Q_{Air}, the total intake flow can be calculated as:

$$Q_{in} = Q_N + Q_{Air} \tag{1}$$

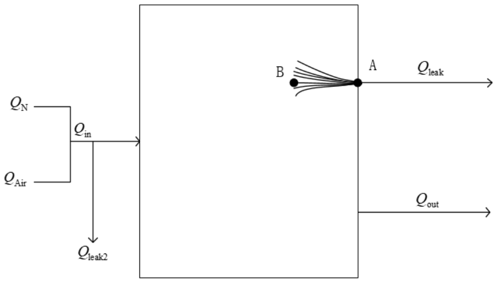

Figure 2: Flow diagram of the bell furnace

The oxygen content is influenced by both the intake and extraction flow. In the period of time *Δt*, the intake mixed gas brings in oxygen at the ratio of a set value, namely, input of the system *u(t)*, and the extraction gas takes out oxygen in proportion to oxygen content *y(t)* in the furnace. Considering that there are leak in the furnace and in the pipeline's flanges, the flow of leakage in the furnace is denoted as Q_{leak}, and in the pipeline is denoted as Q_{leak2}. It is assumed that the fluid at the leak satisfies the Bernoulli's equation, so the Q_{leak} can be deduced below taking the leak and its streamline into consideration shown in Figure 2.

The Bernoulli's equation is used here to draw the relationship of pressure, height, flow and gas density at leak point A and point B, which are on the same streamline:

$$p_A + \frac{1}{2}\rho_A v_A^2 + \rho_A g h_A = p_B + \frac{1}{2}\rho_B v_B^2 + \rho_B g h_B \tag{2}$$

Where *v* is the velocity of flow, *ρ* is the density of gas, *p* is the pressure, *h* is the height, subscripts indicate the identification of localization. The pressure at point A is regarded as standard atmospheric pressure, so the pressure difference between A and B is the furnace pressure. The composition of the gas at point A and point B remains the same, resulting in the same density of gas at point A and point B. It is noticed that the velocity of flow at point B is practically zero, so the Bernoulli's equation can be simplified as:

$$\frac{1}{2}\rho v_A^2 - p(t) - \rho g h_B + \rho g h_A = 0 \tag{3}$$

Where *p(t)* is the pressure difference between A and B. According to the typical sintering process, the furnace pressure needs to be a positive value to ensure the oxygen content not influenced by the outside atmosphere, which is achieved by a PID controller, a pressure sensor and an electric butterfly valve. Usually, the pressure in furnace is controlled and stabilized as 1,000 Pa or above during the sintering process. As a result, the *p(t)* in the formula is irrelevant with time *t* and can be replaced as a constant value noted as *p.*

$$\rho = \frac{2p}{v_A^2 + g(h_A - h_B)} \tag{4}$$

Since the furnace uses electricity to heat the materials rather than fuel, the majority components of the atmosphere in the furnace are nitrogen and oxygen. The density of gas in the furnace can be deduced as below:

$$\rho \approx \frac{m_{N_2} + m_{O_2}}{V} = \frac{\rho_{N_2} V[1 - y(t)] + \rho_{O_2} V y(t)}{V} = (\rho_{O_2} - \rho_{N_2}) y(t) + \rho_{N_2} \tag{5}$$

Where *V* is the volume of the furnace, and *m* is the mass and its subscript indicates the oxygen or nitrogen. The velocity of flow at the leak can be deduced form Eq(4) and Eq(5).

$$v_A = \sqrt{\frac{2p}{(\rho_{O_2} - \rho_{N_2}) y(t) + \rho_{N_2}} - g(h_A - h_B)} \tag{6}$$

Then, $Q_{leak}(t)$ can be calculated by the multiplying of v_A and the cross-section area*:*

$$Q_{leak}(t) = S v_A = S\sqrt{\frac{2p}{(\rho_{O_2} - \rho_{N_2}) y(t) + \rho_{N_2}} - g(h_A - h_B)} \tag{7}$$

Where *S* is the cross-section area. Based on mass conservation law, the oxygen variation during a period of time *Δt* equals to the intake oxygen minus the output oxygen:

$$Vy(t + \Delta t) - Vy(t) = \Delta t[Q_{in} - Q_{leak2}(t)]u(t) - \Delta t Q_{out} y(t) - \Delta t Q_{leak}(t) y(t) \tag{8}$$

When *Δt* tends to zero, the oxygen content process model is obtained as:

$$Vy'(t) + Q_{out} y(t) + S v_A y(t) = (Q_{in} - Q_{leak2}(t)) u(t) \tag{9}$$

Where *u(t)* is the input of system model, i.e. the oxygen content of intake flow Q_{in}. Knowing the air's oxygen content *η*, which usually varies from 16 % to 21 % with different latitudes, *u(t)* can be derived as below:

$$u(t) = \frac{\eta Q_{Air}(t)}{Q_{in}} \tag{10}$$

As for the oxygen control system of the bell furnace, the leakage of furnace can be offset by the electric butterfly valve because its opening degree is always larger than the leakage size, the valve can decrease or increase its opening degree proportionately while the leakage increase or decrease. The leakage of pipeline and its flanges can also be deduced in the same way, and it can be ignored because the leak's size is negligible compared with the pressure, density or oxygen content by orders of magnitude. In the pressure steady state, it is reasonable to consider that Q_{out} approximately equals to Q_{in} for maintaining the constant pressure, and the pipeline leakage only counts an insignificant portion which can be omitted. So the transfer function is deduced by taking Laplace transform for Eq(9) as below:

$$F_1(s) = \frac{Y(s)}{U(s)} = \frac{1}{\frac{V}{Q_{in}}s+1} \tag{11}$$

It will take a period of time for input mixed gas to diffuse to the whole furnace space. The delaying time can be denoted as τ, it is determined by the structure parameters of bell furnace, the temperature, and other relevant condition about gas diffusing. With it the transfer function can be modified as:

$$F(s) = F_1(s)e^{-\tau s} = \frac{1}{\frac{V}{Q_{in}}s+1}e^{-\tau s} \tag{12}$$

3. Simulation and experiment

The nitrogen, which is mixed with air at an oxygen content of 16.98 %, is used to be the input gas, then the oxygen content of the mixed gas is regarded as the input *u(t)* of the system.

A real bell furnace is applied in the experiment in which both the pipeline leakage and the furnace leakage exist caused by assemble tolerance. The experiment results can demonstrate the proposed model is fit to the reality or not. In this experiment, an oxygen content analyser is used to detect the oxygen content, and the relationship between the analyser's output voltage and the actual oxygen content is (Lv, 2013):

$$V_m = 48.26\log\frac{16.98}{PO_2} \tag{13}$$

Where V_m is the output voltage of the oxygen content analyser and PO_2 is the oxygen content. The oxygen content of the air in the experiment is 16.98 %, and when the step input of this system is 12 %, according to Eq(13) the corresponding amplitude of the step input is 7.3 mV.

The results of the step response simulation based on Eq(12) and of the actual measured are shown in Figure 3. The delay time in this experiment is determined by step response, it can be chosen as the interval between the beginning and the time that data start to change. It is 250 s based on step response and the flow of input is set as 80 L/min. Figure 4 shows the absolute error between the simulation result and measured data.

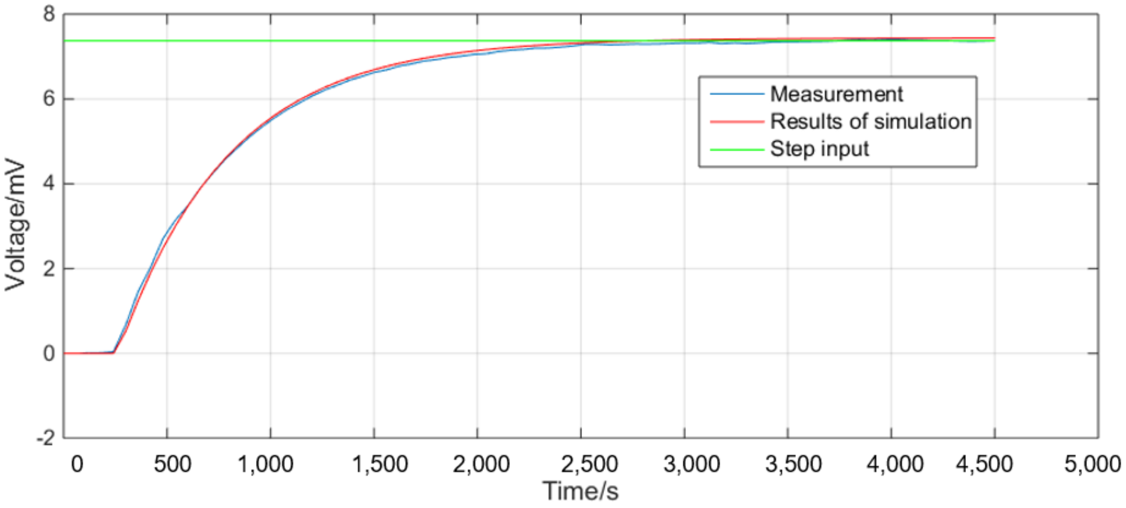

Figure 3: The step response of the process system and model

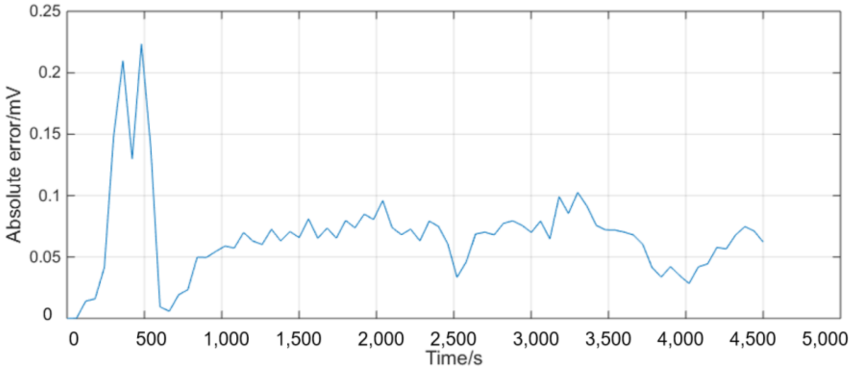

Figure 4: Absolute error between industrial data and simulation results of the step response

In Figure 3, the blue line illustrates the voltage from measured data, and the red line represents the simulation result of the process model. The simulation results are in accord with industrial data under the average error of 0.0671 mV as shown in Figure 4.

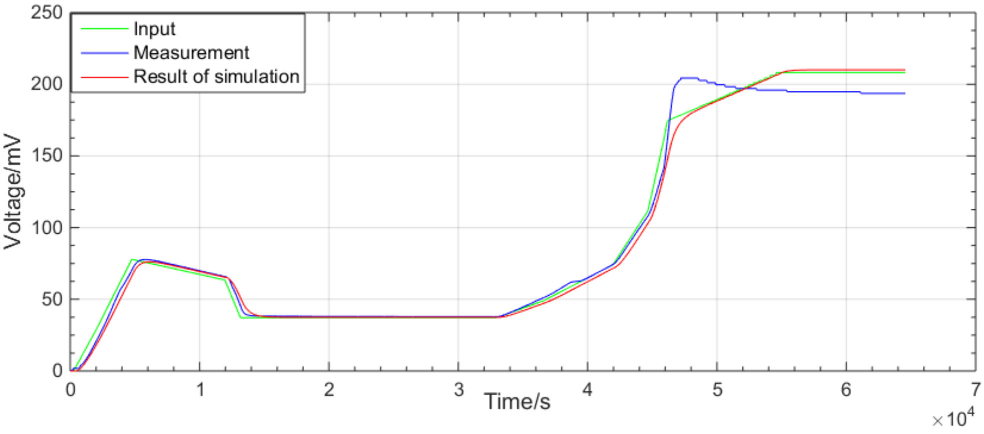

Figure 5: The sintering craft response of process system and model

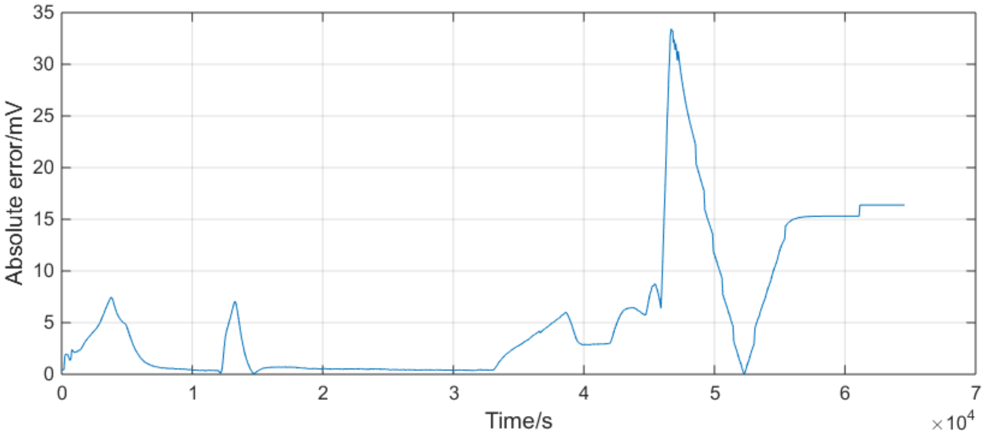

Figure 6: Absolute error between industrial data and simulation results of sintering craft response

The average error between simulation results and measured data is 2.1819 mV when the time is from 0 s to 46,000 s as Figure 6 shows, and the average error is 15.5385 mV while the time is from 46,000 s to the end. The output of the model is obviously different from measured data after 46,000 s for the reason that when the total flow of input is 80 L/min and the input *u(t)* is less than 0.01 %, the air flow should be 0.039 L/min according to Eq(10). However, the accuracy of mass flow controller used in the air intake pipeline is limited by its resolution, when the object is below the resolution the output will be imprecise, which results in a turnoff when the input $u(t)$ is less than 0.01 %. Besides, the flow of leakage is nonnegligible under the circumstance of low oxygen content as Eq(7) refers to. The process model obtained by mechanism modeling is not suitable in such circumstance.

4. Conclusions

This paper deduced the relationship between the oxygen content and the flow of the bell furnace's pipeline. Under time-invariant parameters assumption, such as pressure, furnace volume and flow of the pipeline, this paper analysed the leak's flow of the small crack according to Bernoulli's equation, and established the oxygen content process model of the bell furnace. Then the model was linearized under the negligible pipeline leakage assumption and the furnace leakage offsetting by the pressure regulator, the transfer function of the simplified model was obtained by Laplace transform. The experiment results showed that the model was consistent with the oxygen content process system of the bell furnace when the oxygen content was above 0.01 %. The shut down of the actuator led to the remarkable error with the oxygen content decreasing below 0.01 %, and the influence of the pipeline leak could not be ignored when the oxygen content decreased to an extremely low scale. In this case, the proposed simplified model was no longer reliable. Methods of nonlinear system might be in use to fix the nonlinearity brought by big crack and by oxygen content sensor in close loop control system modelling, researches on that will be valuable.Through the comparison between the simulation results of that simplified model and the experiment results, effectiveness and authenticity of proposed model were proved within a certain range of oxygen content, and can be applied in oxygen content control system.

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