Comparison of the work of Reskvik, Smith, PI regulators in the circuit of maintaining the temperature in a fluidized-bed furnace

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Abstract. This paper dwells upon fluidized-bed furnaces. It shortly describes the theory behind the firing process. Special emphasis is put on calculating the air feed through the nozzles. These calculations serve as the basis for compiling the material and heat balance formulas. The process is modeled mathematically in MatLab. The main parameter of the firing process is the bed temperature. It has been found out that raising the concentrate firing temperature beyond 1050°C enlarges the cinder pieces due to flashing while lowering it below 800°C results in excessive size reduction and incomplete oxidation of the sulfides, i.e. in a worse performance of the furnace. The analysis of firing nickel concentrate in a fluidized-bed furnace shows that for the process to occur appropriately, it is advisable to design the following systems for the automatic control and adjustment of process parameters that determine the quality of firing nickel sulfide concentrate: automatic fluidized-bed temperature control systems, junction-box air feed control systems, and under-roof rarefaction controls. The paper compares three types of controllers as deployed on the furnace temperature maintenance loop.

1. Introduction
As a control object, a fluidized-bed furnace is a continuous multidimensional and multiobjective dynamic object. Uncontrollable disturbances, lack of instant updates on the quality of cinders and a significant (up to 2–3 hours) delay of reports on the initial charge composition make appropriate control and management of the firing process an excruciatingly challenging problem

2. Mathematical Model
Charge is treated in two steps: first it is fired to remove sulfur; then nicked monoxide is reduced with carbon.

The first operation aims to convert as much sulfide and metal into an oxide and to remove as much sulfur as possible.

Purity must be ensured, as subsequent reduction of the oxide will not affect most of the impurities. The firing temperature is 1050°C. Since the concentrate mostly consists of sulfides, the oxidation reactions determine the firing quality in general:

\[ \text{Ni}_3\text{S}_2+5.5\text{O}_2=3\text{NiO}+2\text{SO}_2 \]
Oxidation of the Ni\textsubscript{3}S\textsubscript{2} grains is diffusional. Diffusion occurs in the gas bed. Then the Ni\textsubscript{3}S\textsubscript{2} grains become covered with a NiO film, through which oxygen and sulfur dioxide must diffuse to further oxidize the sulfide core. Therefore, the whole reaction process depends on the rate at which the gas component penetrates the grain.

The key feature of the whole process is that there is no stable temperature range that would separate the onset of nickel-sulfide oxidation and melting. As a result, the material becomes sintered, its pieces enlarged. Such agglomeration is favorable for the remaining concentrate processing steps. This is why finding such parameters, at which the material pieces are enlarged as much as possible while not being sintered and stuck at the bottom, is one of the main challenges today. It is imperative to create automatic control system for this process to keep temperatures within a narrow range on the verge of sintering.

This requires knowledge of the physical and chemical basics of the nickel firing process.

To describe the process as if occurring in a container, let us assume the following idealized model:

1. the concentration of the burning component is the same anywhere in the bed;
2. solid particles and the gaseous phase are evenly mixed;
3. injected air is evenly distributed across the bed;
4. the gas flow rate and pressure are the same across the bed (vertically) and are equal to their actual means;
5. gas pressure and velocity are the same across the fluidized bed (vertically) and are equal to their actual means.

Let us assume the fundamental reaction:

\[ \text{Ni}_3\text{S}_2 + 3.5\text{O}_2 = 3\text{NiO} + 2\text{SO}_2. \]

The reaction rate can be written as:

\[ W = K C_o C_s, \quad (1) \]

where \( K \) is a conditional constant of the chemical reaction rate,

\[ K = K_0 \exp\left(-\frac{E_a}{R(t_{bed} + 273)}\right). \quad (2) \]

where \( K_0 \) is the coefficient of the reaction rate constant; \( E_a \) is the energy of activation, kJ/mole; \( R \) is the gas constant, kJ/(mole-°C); \( t_{bed} \) is the bed temperature, °C; \( C_o \), \( C_s \) are the concentrations of the burning components (oxygen in the reject gases and sulfur in the bed, respectively), mass fraction:

\[ C_s = \frac{G_{\text{fired}} C_{s,\text{fired}} + G_{\text{dust}} C_{s,\text{dust}}}{G_{\text{fired}} + G_{\text{dust}}} = 0.00325. \quad (3) \]

Since the difference between the inflows and the outflows depends on the burnout rate, then:

\[ G_{\text{in}} - G_{\text{out}} = \alpha m_{\text{bed}} KC_o C_s \]

\[ G_{\text{in}} - G_{\text{out}} = \alpha m_{\text{bed}} KC_o C_s \quad (4) \]

where \( G_{\text{in}} \) is the injected-air oxygen flow, kg/s; \( G_{\text{out}} \) is the flow of oxygen carried by the reject gases, kg/s; \( G_{\text{in}} \) is the charge-sulfur flow kg/s; \( G_{\text{out}} \) is the flow of sulfur with the fired products, kg/s; \( \alpha \) is the stoichiometric factor; \( m_{\text{bed}} \) is the weight of the bed, kg.

The expressions in the system (3) define the conditions for the steady burnout of each component under consideration. The system (3) can be considered as the general case of the problem above with the boundary conditions \( C_{O_2} = \text{const} \), as the stationarity of the process is disrupted by the load fluctuations as well as by the instability of the injected-air flow.

Given that the oxygen inflow is the injected-air flow while the outflow is the reject-gas flow, there is:
Let us write the oxygen balance as a function of injected-air and gas flows:

\[ G_{\text{blow}} - G_{\text{gas}} = \alpha m_{\text{bed}} K_0 \exp(-\frac{E_a}{R(t_{\text{bed}} + 273)}) C_{O_2} C_s. \]  

(5)

where \( C_{O_2}, C_s \) - the concentration of oxygen in the injected-air and in the reject gases, fractions.

As \( G_{\text{gas}} = \gamma G_{\text{blow}}, \) then:

\[ C_s = \frac{G_{\text{blow}}}{\alpha m_{\text{bed}} K_0 \exp(-\frac{E_a}{R(t_{\text{bed}} + 273)}) C_{O_2} + \gamma G_{\text{blow}}}. \]  

(7)

\[ \gamma = \frac{G_{\text{gas}}}{G_{\text{blow}}} = 1.0448. \]  

(8)

Given that the sulfur inflow is the flow of sulfur as part of the charge, while the outflow is the sulfur contained in the cinder and in the dust. Then:

\[ G_{s,\text{charge}} - (G_{s,\text{fired}} + G_{s,\text{dust}}) = m_{\text{bed}} K_0 \exp(-\frac{E_a}{R(t_{\text{bed}} + 273)}) C_{O_2} C_s + \gamma G_{\text{blow}}. \]  

(9)

or

\[ G_{s,\text{charge}} - (G_{s,\text{fired}} + G_{s,\text{dust}}) = m_{\text{bed}} K_0 \exp(-\frac{E_a}{R(t_{\text{bed}} + 273)}) C_{O_2} C_s + G_{\text{blow}}. \]  

(10)

The thermal performance of the device depends on the heat generated when charge sulfur burns and carried away with the cinder, dust, gases, etc. Thus, the thermal equilibrium condition can be written as follows:

\[ c_{T_{\text{charge}}} G_{\text{charge}} + c_{T_{\text{blow}}} G_{\text{blow}} + c_{T_{\text{dust}}} G_{\text{dust}} + q m_{\text{bed}} K C_s C_{O_2} - c_{T_{\text{fired}}} G_{\text{fired}} = 0 \]

\[ = \hat{\lambda} - c_{T_{\text{gas}}} G_{\text{gas}} - c_{T_{\text{external}}} G_{\text{external}} - c_{H_{2}O} (c_{H_{2}O} (t_{\text{gas}} - 100)) - G_{\text{blow}} = 0 \]  

(11)

where \( c_{T_{\text{charge}}}, c_{T_{\text{blow}}}, c_{T_{\text{dust}}}, c_{T_{\text{fired}}}, c_{T_{\text{gas}}} \) - the specific heat capacity of the charge/injected air/cinder/reject gases, \( kJ/kg{\text{deg}}; \)

\( G_{\text{charge}}, G_{\text{blow}}, G_{\text{fired}}, G_{\text{gas}}, G_{\text{external}}, G_{H_{2}O} \) - the amount of charge, injected air, cinder, reject gases, external heat losses, and moisture in charge per unit of time, \( kg/s; \)

\( t_{\text{charge}}, t_{\text{blow}}, t_{\text{fired}}, t_{\text{dust}}, t_{\text{gas}} \) - the temperature of charge, injected air, cinder, dust, and gases, \( ^{\circ}{C}; \)

\( q \) is the averaged thermal effect of the oxidation reactions, \( kJ/kg. \)

As the cinder temperature equals that of the bed while the gas/dust temperature is 30 degrees lower, then:

\[ c_{T_{\text{charge}}} G_{\text{charge}} + c_{T_{\text{blow}}} G_{\text{blow}} + c_{T_{\text{dust}}} G_{\text{dust}} + q m_{\text{bed}} K_0 \exp(-\frac{E_a}{R(t_{\text{bed}} + 273)}) C_{O_2} C_s - \\
- c_{T_{\text{fired}}} G_{\text{fired}} = 0 \]

\[ = c_{T_{\text{gas}}} G_{\text{gas}} + c_{T_{\text{external}}} G_{\text{external}} - c_{H_{2}O} (c_{H_{2}O} (t_{\text{gas}} - 100)) - G_{\text{blow}} = 0 \]  

(12)

Thus, the steady state of the furnace is determined by a system of three balance equations:
1) \[ c^\text{prelim} \cdot i^{\text{char,} \text{G}} + c^\text{blow} \cdot t^\text{blow} \cdot G^\text{blow} + c^\text{dust} \cdot t^\text{dust} \cdot G^\text{dust} + qm_{\text{bed}} \cdot K_0 \cdot \exp\left(-\frac{E_a}{R(t_{\text{bed}} + 273)}\right) \cdot C_{O_2} \cdot C_s - c^\text{fired} \cdot t^\text{dust} \cdot (t_{\text{bed}} \cdot G^\text{fired} \cdot G^\text{charge} + t_{\text{bed}} \cdot (G^\text{charge} \cdot G\text{dust})) - c^\text{ext} \cdot (t_{\text{bed}} - 30) \cdot G^\text{blow} \cdot G^\text{charge} \cdot k_{\text{R,O}} \cdot (c_p^\text{H,O} \cdot (100 - t^\text{charge}) + \lambda + c_p^\text{sup} \cdot (t_{\text{bed}} - 30 - 100)) - G_{\text{external}} = 0 \]

2) \[ G_{\text{charge}} \cdot C_s^\text{charge} = (G^\text{fired} \cdot C_s^\text{fired} + G^\text{dust} \cdot C_s^\text{dust}) = m_{\text{bed}} \cdot K_0 \cdot \exp\left(-\frac{E_a}{R(t_{\text{bed}} + 273)}\right) \cdot C_{O_2} \cdot C_s + \gamma G_{\text{blow}} \]

3) \[ C_s^{\text{gas}} = \frac{G_{\text{blow}} \cdot C_{\text{blow}}}{a \cdot m_{\text{bed}} \cdot K_0 \cdot \exp\left(-\frac{E_a}{R(t_{\text{bed}} + 273)}\right) \cdot C_{O_2} \cdot C_s + \gamma G_{\text{blow}}} \]

In a dynamic state, the system will be as follows:

1) \[ \frac{d}{d\tau} \cdot m_{\text{bed}} = c^\text{prelim} \cdot i^{\text{char,} \text{G}} + c^\text{blow} \cdot t^\text{blow} \cdot G^\text{blow} + c^\text{dust} \cdot t^\text{dust} \cdot G^\text{dust} + qm_{\text{bed}} \cdot K_0 \cdot \exp\left(-\frac{E_a}{R(t_{\text{bed}} + 273)}\right) \cdot C_{O_2} \cdot C_s - c^\text{fired} \cdot t^\text{dust} \cdot (t_{\text{bed}} \cdot G^\text{fired} \cdot G^\text{charge} + t_{\text{bed}} \cdot (G^\text{charge} \cdot G\text{dust})) - c^\text{ext} \cdot (t_{\text{bed}} - 30) \cdot G^\text{blow} \cdot G^\text{charge} \cdot k_{\text{R,O}} \cdot (c_p^\text{H,O} \cdot (100 - t^\text{charge}) + \lambda + c_p^\text{sup} \cdot (t_{\text{bed}} - 30 - 100)) - G_{\text{external}} = 0 \]

2) \[ \frac{d}{d\tau} \cdot m_{\text{bed}} = \frac{m_{\text{bed}}}{t^\text{charge}} \cdot C_{\text{charge}} = (G^\text{fired} \cdot C_s^\text{fired} + G^\text{dust} \cdot C_s^\text{dust}) = m_{\text{bed}} \cdot K_0 \cdot \exp\left(-\frac{E_a}{R(t_{\text{bed}} + 273)}\right) \cdot C_{O_2} \cdot C_s + \gamma G_{\text{blow}} \]

3) \[ C_s^{\text{gas}} = \frac{G_{\text{blow}} \cdot C_{\text{blow}}}{a \cdot m_{\text{bed}} \cdot K_0 \cdot \exp\left(-\frac{E_a}{R(t_{\text{bed}} + 273)}\right) \cdot C_{O_2} \cdot C_s + \gamma G_{\text{blow}}} \]

where \( \tau \) is the current time, \( s \).

3. Synthesizing a Temperature Controller

Review of literature reveals [1-5] that the control actions to adjust the furnace temperature may involve both the inflow and the composition of materials.

The injected air flow has a twofold effect on the firing temperatures, as it affects both the inflow of oxygen to the reaction area and the loss of oxygen with the reject gases (which is the most substantial component of the heat balance). Besides, altering the injected air flow affects the hydrodynamic conditions of the fluidized bed, which in turn affects all the mass and heat transfer processes in firing. This is why operators usually want to stabilize this variable at a level matching the furnace performance.

Sulfur content of the charge depends on how the concentrate and the recycled dust are mixed. The way the mixing process is implemented hardware-wise usually prevents any kind of intervention. Besides, the range of adjusting this variable is rather limited. The “lower” limit is due to the “fuel” deficit; the “upper” limit is due to the fact that the when the particles of high-sulfur charge enter the reaction space, they glue so fast that the bed fluidization ceases, causing an emergency.

Furnaces use non-enriched injected air; as such, altering the injected oxygen amounts for control purposes is not recommendable.

Speaking of the state of the art, it is only the inflow of the charge itself that can be altered for such purposes.

A dynamic furnace model has been implemented in MatLab Simulink. PI controller, Smith predictor, and Reskvik [1, 6] controller have been compared by using them to control the in-furnace temperature by adjusting the charge inflow. Figures 1 and 2 present the comparative analysis of these controllers when sending a positive/negative 10% signal to adjust the charge flow.
Figure 1. Comparative analysis of three controllers: 10% positive charge-flow adjustment signal

Figure 2. Comparative analysis of three controllers: 10% negative charge-flow adjustment signal

All three controllers are nearly identical in terms of adjustment time, overshoot, and static errors; however, the PI controller is easier to configure, which constitutes a considerable advantage.

4. Conclusion
FB furnaces are advantageous for firing due to their high performance, firing stability, improved cinder quality, higher concentration of SO$_2$ in gases (which improves the utilization rate of the gases further used in the production of H$_2$SO$_4$), easier preparation of the charge, and easier maintenance (since such
furnaces can be mechanized and automated). However, they also have one serious shortcoming, which is that they tend to produce too many “skulls” when firing materials prone to sintering.

The paper presents material and heat balance calculations based on the firing theory data. As to automation, the researchers have analyzed a fluidized-bed furnace as a control object and compared three types of controllers when used in the temperature maintenance loop.

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