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Blast Furnace Stove Control

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Abstract

This paper outlines the process model and model-based control techniques implemented on the hot blast stoves for the No. 7 Blast Furnace at the Inland Steel facility in East Chicago, Indiana. A detailed heat transfer model of the stoves is developed. It is then used as part of a predictive control scheme to determine the minimum amount of fuel necessary to achieve the blast air requirements. The controller also considers maximum and minimum temperature constraints within the stove.

1. Process Description

A blast furnace is used to produce molten pig iron from iron oxides, coke, and slag. One of the major sources of energy for this process is the sensible heat coming from the preheated air, referred to as blast air, that is injected into the furnace. This air is preheated in tall, cylindrical, refractory-filled heat exchangers called hot blast stoves. These stoves go through alternate cycles of heating and cooling referred to as 'on-gas' and 'on-blast' cycles respectively.

During the on-gas cycle, the stove is heated by the combustion of fuel gas in the combustion chamber of the stove. The combustion products rise to the top of the stove, called the dome, and then descend down through a checkerwork arrangement of refractory bricks, referred to as the checkers. For the on-blast cycle, the flow through the stove is reversed. Air passes up through the checkers, where it is heated, into the dome, and then downward into the combustion chamber. The temperature of the blast air is controlled by diverting part of the flow directly into the combustion chamber to mix with the heated air.

2. Control Objectives

The principle fuel for the hot blast stoves is the carbon monoxide and hydrogen contained in the top gas coming from the blast furnace. In order to achieve the required blast air temperature, however, the top gas must be enriched with a higher heating value fuel. Natural gas is presently being used at the East Chicago facility. The key to reducing the operating cost of the hot blast stoves is to minimize the use of natural gas. This minimization has to take into account the changing blast air flow rate and temperature requirements that must always be achieved for proper operation of the blast furnace.

3. Process Model

The blast furnace stoves are modeled by assuming the channels in the checkers can be represented as thick walled tubes in which the gas flows through the center of the tube heating or cooling the wall material. The outside wall of the tube is assumed to be perfectly insulated. Each tube is divided into five sections representing the five zones in the stove that contain different material type checkers.

The number of tubes used to represent a stove is the number of gas channels in the checkers. This value, denoted by N_c, is the same for each of the five zones and specified by the stove manufacturer. The radius of the gas channel in the tube, r_i, is one half of the hydraulic diameter of the gas channels in the corresponding checker. The outside radius of the tube, r_o, is determined from the total number of gas channels, N_c, the hydraulic diameter of the gas channel, D_h, the total mass and density of the checkers in the corresponding zone, m_z and ρ_z, and the length of the zone, L_z. Each of these values is specified by the stove manufacturer.

$$r_o = \sqrt{m_z/(\pi \rho_z N_c L_z) + D_h^2/4} \tag{1}$$

3.1. Gas Model

The blast air and waste gas are modeled by an energy balance over the gas flowing through a single tube. Assuming the blast air and waste gas are ideal gases, no radial variation of the gas temperature, and no heat conduction in the axial direction results in the following partial differential equation [1]

$$\rho_g C_v \left[\frac{\partial T_g}{\partial t} + v_g \frac{\partial T_g}{\partial z}\right] + P\frac{\partial v_g}{\partial z} - \frac{4h}{D_h}(T_g - T_w) = 0 \tag{2}$$

in which T_g is the temperature, v_g is the axial velocity, ρ_g is the density, C_v is the heat capacity, P is the pressure, D_h is the hydraulic diameter of the channel, h is the gas-solid heat transfer coefficient, and T_w is the solid wall temperature.

The heat capacity is determined by interpolating functions over the operating temperature range of the stove. The density is determined assuming an ideal gas in which M_g is the average molecular weight of air for the on-blast cycle or a nominal waste gas composition for the on-gas cycle. The gas velocity is determined from the inlet mass flow rate, $\dot{m}$, gas density, and cross-sectional area of the gas channel assuming a uniform flow distribution through the checkers.

$$\rho_g = \frac{M_g P}{R T_g}, \qquad v_g = \frac{4\dot{m}}{\pi \rho_g N_c D_h^2} \tag{3}$$

The inlet mass flow rate is determined from the blast air flow rate for the on-blast cycle or from the combustion air and fuel gas flow rates for the on-gas cycle.

The gas-solid heat transfer coefficient is comprised of a contribution from convection and radiation. The convective contribution is determined from a correlation for rough pipes [2]. The radiation contribution is determined from a gas temperature correlation [3].

3.2. Solid Model

An energy balance over a single tube results in the following equation for the solid wall material [1]

$$\rho_s C_p \frac{\partial T_s}{\partial t} - \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T_s}{\partial r}\right) - k\frac{\partial^2 T_s}{\partial z^2} = 0 \tag{4}$$

in which T_s is the temperature, ρ_s is the density, C_p is the heat capacity, and k is the thermal conductivity. The heat capacity and thermal conductivity of each of the five checker material types is specified as a function of temperature by the stove manufacturer.

3.3. Model Calculation

The gas temperature boundary condition for Eq. 2 is the measured temperature of the inlet blast air for the on-blast cycle and the calculated waste gas temperature, from an energy balance, for the on-gas cycle. The initial solid temperature profiles for the on-blast and on-gas cycles are determined from the state of the stove after the preceding cycle and the pressurization and blow-down steps performed on the stove. The stove is pressurized with air prior to the on-blast cycle in order to achieve blast furnace pressure. The solid and gas temperatures are determined by removing the energy necessary to heat the pressurization air in order to achieve local thermal equilibrium. After the on-blast cycle, the stove is returned to atmospheric pressure by venting the contents. The energy lost is determined by assuming an isentropic expansion in the combustion zone of the stove. Details of the numerical solution of the model are provided in [4].

4. Control Algorithm

The optimal on-gas cycle of the stove uses the minimum amount of enriched fuel necessary to achieve the required blast air flow and temperature for the next on-blast cycle. This minimum represents the point where no blast air is by-passed to the combustion chamber to mix with heated air exactly at the end of the cycle. In practice, a small amount of additional heat is put into the stove to ensure that the blast requirements are met. This additional heat can be measured using the by-pass valve position at the end of the cycle. Previous work proposes an on–off control policy for the natural gas enrichment of each stove [5]. This policy is not implementable at the East Chicago facility since natural gas flow cannot be independently set for each stove and the waste gas must be kept above a minimum temperature constraint for pulverized coal drying.

The predictive controller in this work uses the stove model to minimize the enriched fuel flow during the on-gas cycle while respecting the stove temperature constraints and a minimum by-pass value position constraint. This control objective is stated as the following optimization problem solved on-line

$$\min F \tag{5}$$

$$\text{Subject to:} \quad \begin{array}{lcl} F_{\min} & < F < & F_{\max} \\ T_{\min} & < T_j < & T_{\max} \\ V_{\min} & < V & \end{array} \tag{6}$$

in which F is the enriched fuel flow rate profile, T_j are the measured stove temperatures, and V is the by-pass valve position. A second predictive controller attempts to minimize the natural gas enrichment to each stove by adjusting the target of the fuel gas heating value controller that sets the natural gas flow to maintain a constant fuel heating value.

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