On-line Estimation of the Ore-to-coke Ratio in the Blast Furnace Center

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The burden distribution in the blast furnace is of central importance for achieving an energy-efficient operation of the process. In spite of the fact that a number of measuring devices have been developed for detecting the burden surface profile, it is difficult to obtain reasonable estimates of the realized burden distribution in operating blast furnaces. Especially in furnaces with bell-type charging equipment, the push effect exerted by heavier materials, such as sinter or pellets, makes the “transformation” of an observed burden surface profile into layer thicknesses unreliable. Another problem is the possible penetration of pellets into previously charged coke layers. These facts are reasons why a number of models for indirect estimation of the burden distribution using “standard” measurements have been proposed. This note briefly presents a method for on-line estimation of the ore-to-coke ratio in the center of the blast furnace. As the main source of information, frequent temperature measurements from an above-burden probe are used. The method is illustrated on data from a Finnish blast furnace.

The proposed method bases its estimation on observations of temperature transients recorded by an above-burden probe, using an approximate equation for the thermal conditions in the upper shaft of the blast furnace as a function of the vertical coordinate, z. It is assumed that there is a region in the furnace shaft where the gas and burden take the same temperature, Tg. The occurrence of a “thermal reserve zone” is generally accepted and is also supported by result of direct measurements. For the sake of simplicity, the model is also based on the assumption that no radial transport of mass or heat, and no major chemical reactions occur in the furnace part considered, and the gas is assumed not to mix between the stockline and the probe. Finally, to further simplify the treatment, the heat capacities of the gas and the burden, cgs and cg, are assumed to be constant. These assumptions, naturally, introduce some inaccuracies into the model, but they are used to make the model complexity manageable for on-line use.

From an energy balance for the region between a position z and the thermal reserve zone, an expression for the thermal (or heat) flow ratio, γ, can be written as

\[ \gamma = \frac{m_c g}{w_s \rho_g c_g} = \frac{T_g - T_g(z)}{T_g - T_g(0)}, \ldots \]

where \( m \) denotes a mass flow, and subscripts s and g refer to the solid and the gas phases. The thermal flow ratio is known to govern the temperatures in the upper shaft of the furnace. From a differential heat balance, the static gas temperature profile can be derived as

\[ T_g(z) = T_g(0) - \gamma(T_g(0) - T_g(0)) \exp\left\{ (\gamma - 1) \frac{ha}{w_s \rho_g c_s} z \right\}, \ldots \]

where \( h \) is the gas–solid heat transfer coefficient, \( a \) is the bed surface per bed volume, and \( w_i \) and \( \rho_g \) are the descent rate and the bulk density of the burden, respectively. If the reserve zone temperature, \( T_R \), is known it is possible to replace \( T_g(z) \) and \( T_g(0) \) in Eq. (2) using Eq. (1). After some algebra, the equation for the profile simplifies to

\[ T_g(z) = T_R - \gamma(T_R - T_g(0)) \exp\left\{ (\gamma - 1) \frac{ha}{w_s \rho_g c_s} z \right\}, \ldots \]

The derivative of Eq. (3) with respect to \( z \) is

\[ \frac{dT_g}{dz} = -(\gamma - 1) \frac{ha}{w_s \rho_g c_s} \gamma(T_R - T_g(0)) \exp\left\{ (\gamma - 1) \frac{ha}{w_s \rho_g c_s} z \right\} \]

which can be considerably simplified by combination with Eq. (3), yielding

\[ \frac{dT_g}{dz} = (T_R - T_g)(\gamma - 1) \frac{ha}{w_s \rho_g c_s}, \ldots \]

Further, since the model is based on observations of the top gas temperature, we study the gas temperature at the burden surface. The chain rule now yields

\[ \frac{dT_g}{dt} = \frac{dT_g}{dz} \frac{dz}{dt} \quad \text{with} \quad \frac{dz}{dt} = w_s, \ldots \]

since the point of observation follows the burden surface along its descent. Inserting Eq. (6) into Eq. (5) gives an expression that is independent of the spatial coordinate, but instead describes the dynamic response of the gas temperature, \( T_g(t) \), at the stock level (if the gas between the burden surface and the probe is assumed not to mix)

\[ \frac{dT_g}{dt} = (T_g(0) - T_R)(\gamma - 1) \frac{ha}{\rho_g c_s}, \ldots \]

Inserting the heat flow ratio from Eq. (1) with \( z=0 \) finally yields the mean bulk density of the burden

\[ \rho_s = \frac{ha(T_g - T_g(0))(T_g(0) - T_g(0))}{c_s \frac{dT_g}{dt}(T_R - T_g(0))}, \ldots \]

Equation (8) gives a connection between the average bulk
density of the solid phase and the temperature “profile” of the gas phase, where the latter can be tracked through frequent measurements of the top gas temperature. A parameter, \( \alpha < 1 \), has been introduced to consider possible inertia of the measurement device (i.e., probe). Since the mean bulk density depends on the mass flows of ore (subscript o) and coke (subscript c) according to

\[
\rho_s = \frac{\dot{m}_s}{\dot{V}_s} = \frac{\dot{m}_o + \dot{m}_c}{\dot{m}_o / \rho_o + \dot{m}_c / \rho_c}, \quad \text{(9)}
\]

where \( \dot{V}_s \) is the volume flow rate of burden, the ore-to-coke ratio, defined on mass basis, \((o/c)=\dot{m}_o/\dot{m}_c\) can be introduced, yielding

\[
(o/c) = \frac{\rho_c (\rho_o - \rho_c)}{\rho_o (\rho_o - \rho_c)}, \quad \text{(10)}
\]

The ore-to-coke ratio at a certain radial position can thus be calculated from Eqs. (8) and (10) from the (local) gas temperature above the burden surface. Since the model is based on the assumption that the gas should follow the “static” temperature profile in the shaft, the initial transients observed after charging (cold) burden layers should be excluded. In an earlier simulation study\(^{[15]}\) it was concluded that the gas temperature approaches the static profile a few minutes after charging.

The model is illustrated on data from the small (570 m\(^3\)) blast furnace of Fundia Wire Oy Ab in Koverhar, Finland, which has a two-bell top and movable armors. The furnace is operated with 100% pellets, using a four-dump charging program \( P_1/P_2 + C/C_1/C_2 \), with two dumps of pellets followed by two dumps of coke, where the second pellet dump pushes some coke into the central part of the furnace to implement center-coke-charging\(^{[13,14]}\). An above-burden probe with 11 measurement points\(^{[8]}\) was used to record the transients in the gas temperature, but only the center temperature from the above-burden probe was used in the analysis. The reasons for studying this region is that it is important to control the central gas flow and also the passage of the center-charged coke into the dead man, especially since no other measurement devices at the furnace provide information from this region of the cross-section. Also, the gas temperature in the center is high, so the initial transient in the temperature caused by the heating of the latest charged dump and evaporation of accompanying moisture, will be short. Finally, because of the features of the charging program, there will be enough time to exclude initial transients and to observe the approach of the gas temperature to the static temperature profile.

The model is first illustrated on process data from a day in early 2000, using the most frequent probe measurements available in the database, i.e., 30 s averages.

In calculating the mean bulk density, the parameters of Table 1 were used, approximating the derivative of the temperature by central differences. The value of the volumetric heat transfer coefficient, \( h_A \), was selected on the basis of earlier findings.\(^{[19]}\) In agreement with results from a simulation study,\(^{[15]}\) the temperatures used in Eq. (8) were the (estimated) temperature of the charged burden and the mean temperature of the top gas. The effect of the probe dynamics\(^{[8]}\) on the temperature response was considered by using \( \alpha = 0.9 \) in Eq. (8).

The upper panel of Fig. 1 shows the evolution of the centremost temperature, which is seen to vary between 400°C and 800°C. Usually, every second dump results in a considerable temperature drop, so the temperature collapses every 7th minute on an average. It was found that the estimate of the ore-to-coke ratio (and the density) exhibited a minimum when the observed gas temperature stabilized on the exponential profile. In order to exclude the values referring to the initial dynamics but also to the “saturation” observed at high temperatures, which is caused by an increased extent of mixing of the gas between the burden surface and the probe along with the descent of the burden surface,\(^{[16]}\) the following procedure was adopted. After each dump, three consecutive values of the estimated ore-to-coke ratio were not allowed to differ by more than a quantity, \( e \), from the mean value of the three ratios in order to be accepted as a valid value. By this measure odd values of the ore-to-coke ratio could be eliminated. The value of \( e \) was not found to be especially crucial for the estimated value of the ratio; a value of \( e = 1.0 \) was used in this study.

Figure 2 shows the temperature (upper panel) and the calculated ore-to-coke ratio (asterisks in lower panel) for a 1-hour period. The temperatures are seen to follow an exponential behavior after the initial transients. In the lower panel the valid ore-to-coke ratios, selected by the procedure explained above, have been denoted by circles (on top of the asterisks), and they are seen to correspond quite well to the (local) minima exhibited by \((o/c)\).

Occasionally, the intermediate coke dumps \( (C_1) \) may interrupt the temperature rise (e.g., at \( t = 372 \) min in the fig.-

### Table 1. Variables and parameters used in the model.

| Variable | Value         |
|----------|---------------|
| \( T_{cm} \) | 0°C           |
| \( T_b \) | 950°C         |
| \( \rho_o \) | 2100 kg/m\(^3\) |
| \( \rho_c \) | 480 kg/m\(^3\) |
| \( c_i \) | 800 J/(kg K)  |
| \( ha \) | 4.5 kW/(m\(^2\) K) |
ure), probably because of a low stock level, but the simple validity test discards information from such dumps. The remaining observations over the data period, as depicted in the lower panel of Fig. 1, show a mean value of \( \frac{\rho_o}{\rho_c} = 2.58 \), which may be slightly overestimated because of occasional spikes in the observations. However, this value implies that the layer thickness ratio would be \( \frac{l_o}{l_c} = 2.58 \cdot \frac{\rho_c}{\rho_o} = 0.59 \), i.e., 63\% (=1/1.59) of the volume in the furnace center should be occupied by coke. The second pellet dump contained about 650 kg coke and it is likely that most of this coke enters the center of the furnace. Considering this fact, the estimate seems reasonable. In addition, an alternative static model\(^{17}\) developed by the authors yielded an ore-to-coke ratio of about 2 in the center of the furnace. In order to use the model for on-line tracking of the ore-to-coke ratio, it is clear that the estimated values need to be filtered to cancel noise. To illustrate this, the valid \( \frac{\rho_o}{\rho_c} \) observations of the lower panel of Fig. 1 have been passed through a first-order filter, yielding the solid line in the figure.

Some results from a later 5-day period are presented in Fig. 3, where the larger number of observations in the data set illustrates better how the model could be used to track changes in the variable.

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