Blast-Furnace Smelting with Coal-Dust Injection

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Abstract—Smelting in two different blast furnaces is considered on the basis of a multiband model, which relates the processes that affect the smelting conditions to the final outcome. The analysis focuses on conditions in which the coal-dust consumption varies widely, as well as the distribution of materials over the furnace radius. New results and practical conclusions are obtained.

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In the present work, we assess the influence of coal-dust consumption on smelting, from a systems approach. Existing estimates based on empirical data and balance calculations primarily present the relation between the initial parameters and the final results (coke consumption, productivity), with only a few intermediate parameters [1, 2]. They fail to illuminate all the internal relationships that affect the smelting conditions and the outcome.

We assess the consumption of coal-dust fuel on smelting by means of a mathematical model developed at the Institute of Ferrous Metallurgy, Ukrainian Academy of Sciences [3]. The predictive capabilities of this model are expanded on the basis of the structural relationship between the multizone mass and heat balances over the height and the radius of the blast furnace, on the one hand, and the overall mass and heat balances, on the other. On that basis, new quantitative relations between the processes may be established, and the influence of the nonuniform distribution of materials over the furnace radius on smelting may be identified.

MODEL AND METHOD

Heat transfer and reduction of iron in annular zones over the height of the batch column are described in the model by a discrete system of material and heat balances in 12 vertical zones, for intervals of batch temperature from the initial value to 400°C and then in 100°C increments up to the temperature of the smelting products. Each vertical zone is characterized by particular conditions of heat and mass transfer and also by the transition of material from the solid to the liquid phase through a doughy state. In the peripheral annular zone, over the whole height of the batch column, heat losses through the furnace wall are taken into account. The annular zones, which are equal in size over the horizontal charge-hole area, correspond to ten angular positions of the trough in the nonconical charging system. The charging of these zones differs in the ratio of batch components (primarily, the coke and iron ore), which is specified by the loading program and calculated in the charging model. In the charging model, the distribution of each individual iron-ore and coke component in the charge hole is established. This is associated with different batch composition and, correspondingly, with different composition of the slag formed in different radial annular zones. Accordingly, the temperature boundaries corresponding to the onset of softening, melting, and complete liquefaction are determined for each radial annular zone. The dependence of these temperatures on the chemical composition of the batch is determined for each radial annular zone and calculated from the generalized model developed at the Institute of Ferrous Metallurgy, which forms one module within the general multizone model of the blast furnace. In the model, these temperatures are predicted by means of integral convolution criteria for the chemical composition, with subsequent correction in terms of the degree of reduction of the materials and the quantity of alkali oxides (K₂O + Na₂O) introduced in the furnace.

Thus, the batch column is divided into 10 × 12 = 120 conditional cells, for each of which the zonal material—thermal balance, related to the overall material—thermal balance of the furnace, is calculated.

The new approach offers additional scope for the analysis of processes and the formation of measures to increase the efficiency of smelting, such as the identification of the limiting zone over the furnace height and cross section; quantitative allowance for the increased thermal load on the gas flux in the peripheral zone (on account of heat losses); allowance for the gas flows from one radial annular zone to another at different levels; assessment of the reduction process over time, in annular cross sections over the furnace radius; determination of the influence of the radial distribution of materials on the heat losses and also the influence of all the technological factors on the coke consumption, with allowance for the change in the heat losses; and evaluation of the role of the softening and melting zone in the formation of smelting conditions.
and the corresponding temperature-concentration fields of the furnace.

To assess the influence of the coal-dust consumption on the smelting process, we use data regarding the operation of blast furnace 9 at OAO ArcelorMittal Krivoi Rog (useful volume 5000 m³) and blast furnace 5 at OAO Severstal’ (useful volume 5500 m³) in characteristic operating periods (the baseline periods). Discrepancies in the balance of gasified elements in the baseline periods are minimized by correcting the composition of the furnace gas at blast furnace 9 and the oxygen content in the blast at blast furnace 5; these are the parameters most likely to introduce large errors in the results of the analysis. We consider conditions in which the ash and sulfur concentrations in the coal-dust fuel do not exceed the corresponding concentrations in the coke, while the oxygen content in the blast is 25%. For such conditions, by specifying different coal-dust consumption, we may predict the smelting characteristics for two distributions of the ore load over the charge hole: the actual ore load; and the uniform ore load in radial annular zone 2-9.

ANALYSIS OF THE RESULTS

Tables 1–4 present the basic numerical results. In Figs. 1–6, we show the results for processes within the blast furnaces.

With increase in coal-dust consumption, the coke consumption declines. Some of the heat from the coke is replaced by heat from the coal-dust fuel, while the degree of direct reduction is somewhat less, with slight change in furnace-gas temperature, as in the balance calculations [1, 2]. The first component is responsible for more than 80% of the coke savings and does not greatly depend on the smelting conditions. The second component is different for the two furnaces considered and depends on the reduction conditions. In blast furnace 5 at OAO Severstal’, these conditions are closer to limiting (with higher gas utilization), and the diminution in direct reduction is only half as much. Accordingly, the equivalent of coke substitution is somewhat lower at blast furnace 5.

The heat losses through the walls decline smoothly with increase in coal-dust consumption for blast furnace 9 at OAO ArcelorMittal Krivoi Rog (0.05%/m³), with slight change for blast furnace 5 at OAO Severstal’.

For all values of the coal-dust consumption, the differential equivalent of coke substitution (the equivalent in the range of coal-dust consumption from the previous to the current value) is close to the mean in the range 0–250 kg/t of hot metal: 1.0 and 0.9 kg/kg for blast furnaces 9 and 5, respectively. These values are typical with increase in the coal-dust consumption for both the actual and uniform ore-load distributions. With some lowering of gas intensity, the furnace productivity increases, on average, by 0.01%/m³ for furnace 9 and 0.02%/m³ for furnace 5.

The thermophysicochemical principles underlying the observed blast-furnace behavior are illustrated by the results in Figs. 1–6.

The temperature field of the batch and the gas flux within the furnaces changes with increase in coal-dust consumption, as in the injection of natural gas and coke-oven gas [4]. However, in the present case, the changes are less pronounced and they do not depend in a simple manner on the furnace conditions and the batch distribution. Thus, with increase in coal-dust consumption, the batch is heated to the specified temperature at lower levels within the furnace (Fig. 1). As a result, the softening and melting zone descends somewhat, primarily on account of the softening level (Fig. 2). That leads to significant decrease in thickness of the softening and melting zone. At furnace 5, the opposite shift in the temperature field is observed (Fig. 3). However, some decrease in thickness of the softening and melting zone is seen (Fig. 4). The difference is explained by the different properties of the ore and coke in the blast furnaces. In particular, the kinetic constants of heat transfer and reduction are higher in furnace 5 than in furnace 9; the batch density is also different.

Our analysis shows the possibility of ensuring low coke consumption—286–304 kg/t for furnace 9 and 257–276 kg/t for furnace 5—on account of coal-dust injection at rates up to 250 kg/t and improvement in the ore-load distribution. However, such blast-furnace operating conditions cannot be regarded as rational—in particular, in terms of the temperature field, on account of the high theoretical combustion temperature (>2200°C). Especially unfavorable conditions are observed when the coal-dust consumption is less than 250 kg/t (theoretical temperature >2300°C). This problem may best be addressed by the injection of coke-oven gas already produced at the enterprise. Correspondingly, the coke-oven gas used in coke production and in heaters is replaced by blast-furnace gas and products of coal gasification [3].

Calculation results for smelting with the injection of coal-dust fuel and coke-oven gas (Tables 1–4, Figs. 5 and 6), as well as experience with coke-oven gas [3], indicate that this technology is highly efficient and is characterized by an organic relation between the injection of coal dust and coke-oven gas (or another reducing gas). Key considerations here include the following:

— the possibility of organizing a rational temperature field in the furnace, ensuring improved stability of the processes and better heat and mass transfer within the batch column;

— further diminution of the degree of direct reduction, beyond the levels attained in the injection solely of coal-dust fuel;