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Temperature Distribution of the Gas Flux in Blast Furnaces

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Abstract—The distribution of the temperature variation of the gas flux in the peripheral zone over the height (from the bosh to the upper levels of the shaft) and the temperature above the charge surface over the furnace radius was investigated in 2016 at a blast furnace at Metinvest Holding LLC, in various conditions: with gas-free charge and a wet blast; and with natural gas and/or pulverized-coal injection.

Keywords: blast furnaces, pulverized coal, lining-mounted thermocouples, thermal probes, peripheral gas flux

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In recent years, with the rising cost of natural gas, pulverized-coal injection has been adopted at blast furnaces in Ukraine. In the first stage, pulverized-coal injection is generally introduced without any attention to the requirements on coke and iron-ore quality, without preliminary modernization of the cooling and charging systems, and without automation. The effectiveness of pulverized-coal injection depends not only on the quality of the coal and the design of the tuyeres but also on the adoption of appropriate charging conditions [1]. Up-to-date monitoring systems may expediently be used in selecting the best loading conditions.

In a blast-furnace shop at Metinvest Holding LLC (Ukraine), in 2016, the introduction of pulverized-coal injection began at blast furnaces 3 and 5. In the present work, we report research at 1719-m^3 blast furnace 3, which went into operation after reconstruction in October 2011 [2–10]. This blast furnace is equipped with a single-channel nonconical Paul Wurth charging system; four stationary thermal probes above the charge surface [5]; and thermocouples in the shaft lining over the furnace height and circumference [6]. The thermocouples are embedded at a depth of 100 mm in the lining, whose design thickness is 300 mm. They are mounted at six levels over the height of the furnace shaft and also at the bosh extension, bosh, and below the tuyere. Over the furnace circumference, eight thermocouples are located at the bosh and bosh extension and at the three lower levels of the shaft; four thermocouples at the next two higher levels; and four thermocouples at the upper level [6, 7].

After the startup of blast furnace 3 in 2011, the shaft was shotcreted in June 2014. At the beginning of 2016, the lining life was already 1.5 years and, after flushing of the furnace for the next shotcreting in September 2016, visual inspection revealed the practically complete lack of protective lining over the whole shaft handing, as well as a coating band at the bosh level. In such conditions, the thermocouples recorded the gas-flux temperature in the peripheral zone over the working height of the furnace between January and September 2016 [7]. From the temperature variation, we may judge both the influence of the blast on the gas-flux distribution in the furnace and the coating formation (especially in variable operating conditions and at the early stages of the introduction of pulverized-coal injection).

The operation of blast furnace 3 in the 8.5 months of 2016 considered may be characterized by four basic periods:

(1) with gas-free batch and a wet blast, when the vapor consumption was 2.4 t/h, on averaging (January 1 to March 14);

(2) with natural gas, supplied at a mean rate of 58.9 m^3/t of hot metal (March 15 to April 20);

(3) with natural gas (10.8 m^3/t) and with pulverized-coal injection (91.8 kg/t of hot metal), in the early stages of its introduction (April 21 to June 3);

(4) with pulverized-coal injection (129.6 kg/t of hot metal) before furnace shutdown for shotcreting (June 29 to September 13).

In Fig. 1a, we show the temperature distribution of the peripheral gas flux over the furnace height for the four periods. In Fig. 1b, we show the temperature distribution for the fourth period, divided into three intervals with different pulverized-coal consumption.

As we see in Fig. 1, the temperature distribution of the peripheral gas flux over the furnace height is largely determined by the blast and the pulverized-coal consumption. Considering the bottom of the shaft, the

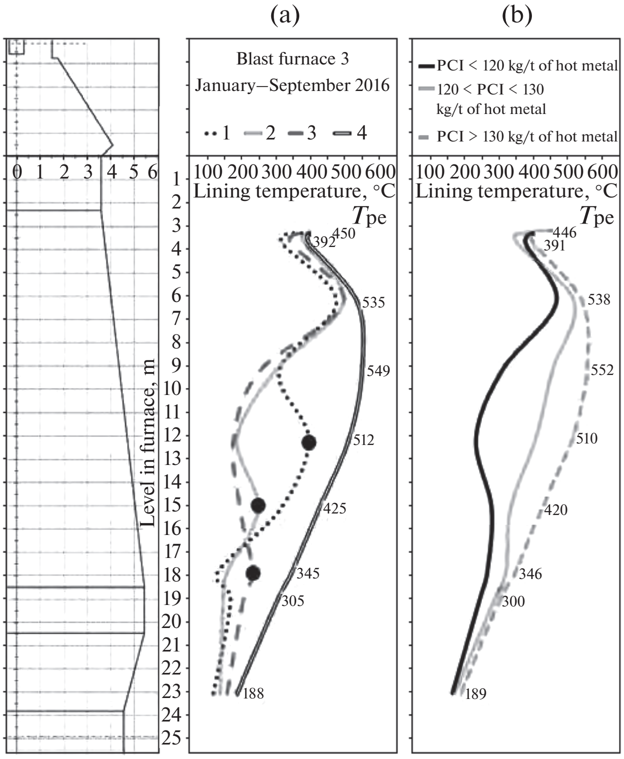

Fig. 1. Temperature distribution of the peripheral gas flux over the furnace height in different conditions: T_{pe} is the peripheral gas flux below the protective plates at the charge hole; (●) extrema on the temperature distribution; PCI, pulverized-coal injection.

bosh, and the bosh extension, we find the maximum temperature at a distance of 12 m from the reference point (the top of the protective plates at the charge hole) or a distance of 13 m from the axis of the air tuyeres in the first period; at a distance of 15 m from the reference point (10 m from the tuyere axis) in the second period; and at a distance of 18 m from the reference point (7 m from the tuyere axis) in the third period. In the fourth period, no distinct extremum was seen in the lower part of the furnace: the gas temperature increased monotonically from the bosh to a distance of 6 m from the reference point.

In our view, the extrema observed in the first three periods correspond to the root of the plastic zone and the boundary of the stable component of the coating that is formed in the furnace. This is confirmed by results obtained on a 3594-m^3 blast furnace at the Thiessen plant [11, 12]. The position and profile of the plastic zone were determined on the basis of the distribution of the pressure, lining temperature, and gas composition at the wall over the furnace height in [11]. At the blast furnace, the lining temperature was determined at 16 levels above the tuyere axis, while the static pressure difference was given at 13 levels. The height of the plastic zone—the distance of its upper boundary above the tuyere level – was 14 m in poor furnace operation, 9 m in fair operation, and 8 m in good operating conditions, according to [11]. The lining temperature was plotted over the furnace height for periods with poor and good operation in [11]. The results largely agree with Fig. 1a. The first three operating periods of blast furnace 3 may also be characterized as periods of poor, fair, and good operation in terms of the daily output and the coke consumption. Note also that, in the first period, the proportion of pellets in the iron-ore mixture (54.8%) was higher than in the other periods, while the large content of high-basicity sinter in the mixture facilitated the formation of a tall plastic zone on account of the fusibility of the pellets. Since the distance from the air tuyeres to the maximum temperature is greatest in the first period, this may be regarded as support for the hypothesis that the upper boundary of the plastic zone is at the point of maximum temperature.

Increase in pulverized-coal consumption at blast furnace 3 (Fig. 1b) raises the gas temperature, with maximum change at the middle of the shaft. The temperature rise is due to intensification of the peripheral gas flux with increase in pulverized-coal consumption. The temperature change is a maximum at the middle of the shaft on account of the increased distance from the tuyere axis and the excellent design of the tuyeres in blast furnace 3.

The next stage in our research is to analyze the correlation of the thermocouple readings (the temperature of the gas flux in the first half of 2016) in blast furnace 3 with the conditions during the 200-day operating period, including the blast conditions. The correlations are determined on the basis of the mean daily thermocouple readings.

Analysis shows (Fig. 2) that the best correlation with the pulverized-coal consumption is obtained for the mean lining temperatures at the bottom of the shaft ($R_{x,y} = 0.78$), at the bosh extension ($R_{x,y} = 0.67$), and at the bosh ($R_{x,y} = 0.80$). In the middle of the shaft (at 28.739 m), where the gas temperature is greatest, the correlation coefficient with the pulverized-coal consumption is $R_{x,y} = 0.62$. Thus, we conclude that the influence of the pulverized-coal consumption on the temperature of the peripheral gas flux is greatest at the bottom of the shaft, at the bosh extension, and at the bosh.

We should also note the following:

(1) the inverse correlation of the lining temperature at the bosh (at 14.930 m) with the skip-coke consumption ($R_{x,y} = -0.76$) and its direct correlation with the mean daily furnace output ($R_{x,y} = 0.66$);

(2) the inverse correlation of the temperature at the bottom of the shaft (at 20.120 m) with the skip-coke consumption ($R_{x,y} = -0.67$);

(3) the correlation of the mean square deviation of the lining temperature at the middle of the shaft

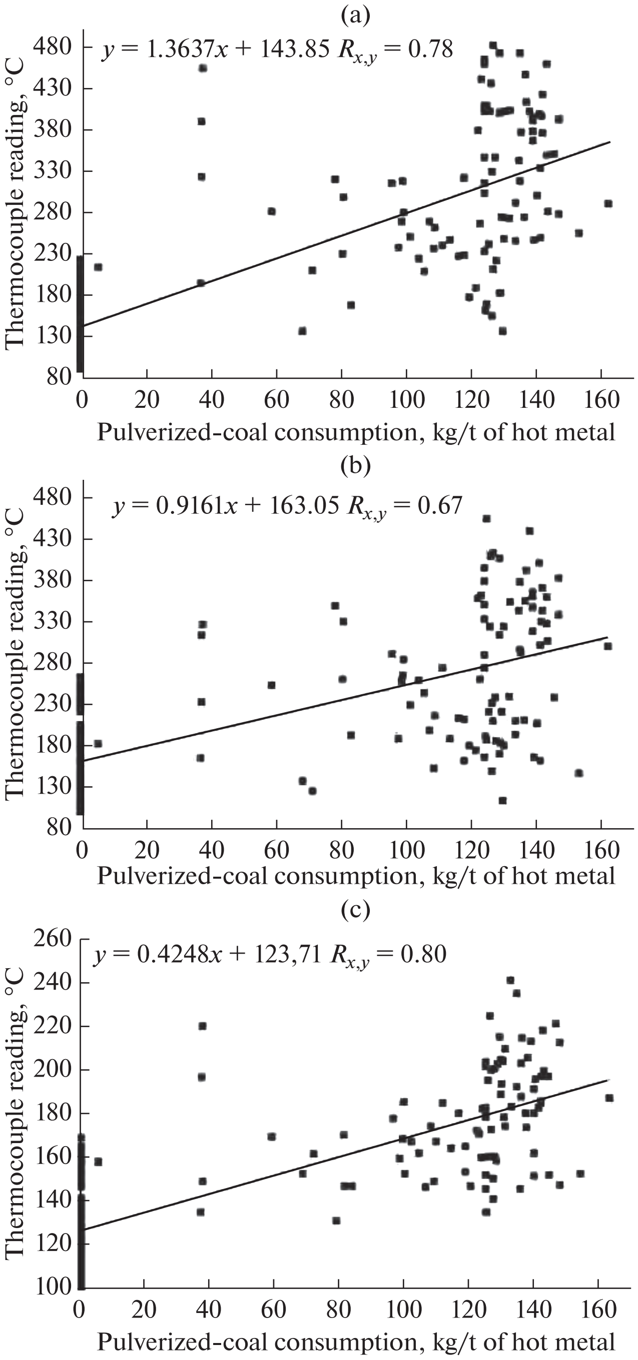

Fig. 2. Dependence of the lining temperature at the bottom of the shaft (a), at the bosh extension (b), and at the bosh (c) on the pulverized-coal consumption for blast furnace 3.

(at 25.878 m and at 28.739 m) with the skip-coke consumption ($R_{x,y} = 0.57$ and 0.78, respectively);

(4) the inverse correlation of the mean square deviation of the lining temperature at the middle of the shaft (at 28.739 m) with the mean daily furnace output ($R_{x,y} = -0.62$);

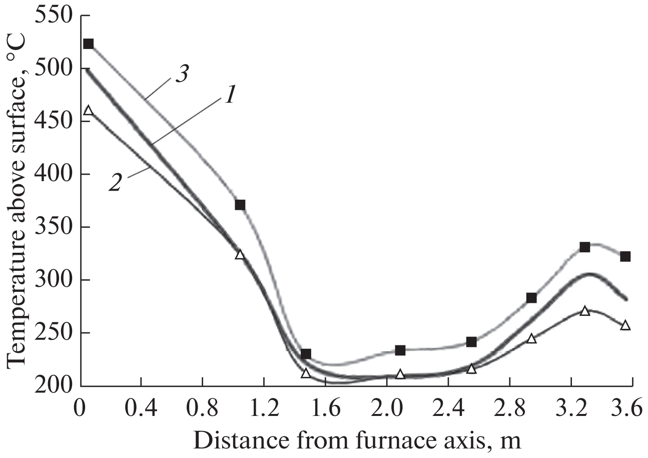

Fig. 3. Temperature distribution of the gas flux above the surface of the charge over the radius of blast furnace 3 for the first three periods.

(5) the inverse correlation of the lining temperature at the middle of the shaft (at 25.878 m) with the natural-gas consumption in the blast ($R_{x,y} = -0.55$);

(6) the inverse correlation of the mean lining temperature at the bottom of the furnace (the bottom of the shaft, bosh extension, and bosh) and at the top of the furnace (the middle and top of the shaft) with the proportion of local sinter in the iron-ore component of the batch ($R_{x,y} = -0.55$ and -0.52, respectively);

(7) the strong inverse correlation between the proportion of local sinter in the iron-ore component of the batch and the lining temperature in the middle of the shaft ($R_{x,y} = -0.59$).

These correlations indicate that the quality of the coke and iron ore affect the lining temperature and also that the gas-flux distribution over the furnace periphery affects the coke consumption of furnace output. The inverse correlation of the lining temperatures at the bosh and at the bottom of the shaft with the coke consumption may be explained on the basis of their direct correlations with the pulverized-coal consumption, since pulverized-coal injection reduces the coke consumption.

The next stage is to analyze the temperature variation over the surface of the charge on the basis of the thermal-probe readings, for the first three operating periods of blast furnace 3. No data are available for the fourth period, since the thermal probes failed in that period, after two years of operation. In Fig. 3, we show the temperature distribution of the gas flux over the radius of blast furnace 3 for the three periods.

As we see, the second period is characterized by the lower temperatures in the peripheral and central zones. In the third period, the temperature is higher than in the first two over the whole furnace cross section. This may be mainly attributed to the lower pellet content in the ore mixture in the third period (38.5%,

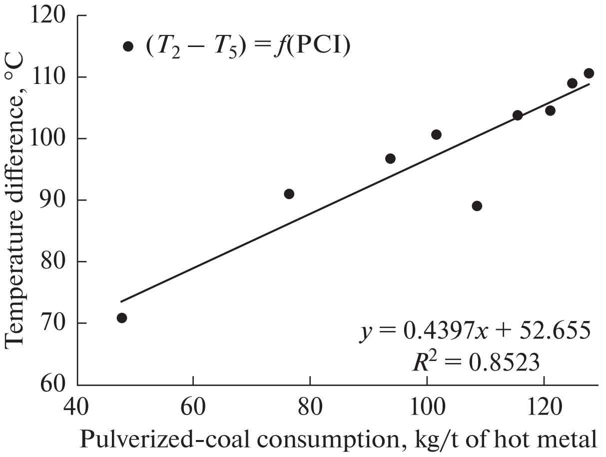

Fig. 4. Temperature difference of the gas flux above the surface of the charge between the peripheral and central zones as a function of the pulverized-coal consumption.

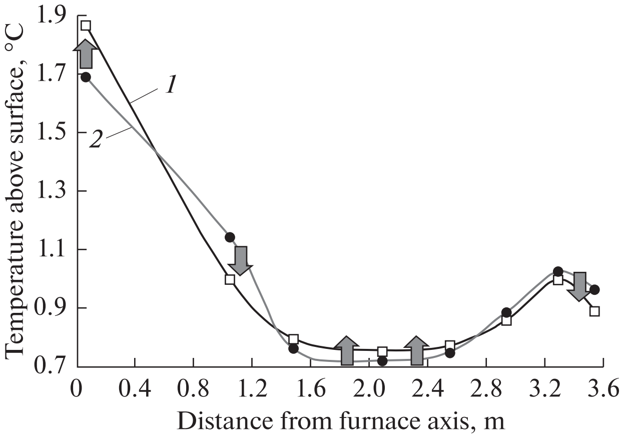

Fig. 5. Temperature distribution of the gas flux above the surface of the charge over the radius of blast furnace 3: (*1*) January–May 2016; (*2*) October 2016, after shotcreting of shaft.

as against 54.8% in the first and 54.4% in the second). That increases the gas temperature above the surface of the charge on account of the higher content of hot sinter in the batch [5]. The temperature difference of the peripheral and central zones in the first and second periods, when the pellet content is practically the same, may be explained in that, for gas-free batch (period 1), the dry zone is smaller than in the presence of natural gas (period 2). That ultimately accounts for the temperature rise in the first period in the two most gas-permeable zones (the peripheral and central zones).

Finally, we analyze the temperature above the surface of the charge as a function of the pulverized-coal consumption. In the fourth period, the pulverized-coal consumption is 128 kg/t of hot metal on some days. When the batch is charged, no changes are seen. Analysis of the gas temperature above the surface of the charge in this period indicates weak interchange of gas between the peripheral and central zones. In pulverized-coal injection, that leads to excessive development of the peripheral gas flux. This is confirmed by analyzing the temperature above the surface of the charge as a function of the pulverized-coal consumption. We find that the difference in gas temperature above the surface of the charge between the peripheral (point 2) and intermediate (point 5) zones of the charge hole is correlated with the pulverized-coal consumption (Fig. 4). That confirms that pulverized-coal injection intensifies the gas flow at the wall, while also hindering gas flow along the furnace radius.

After the repair of blast furnace 3 in September 2016, with shotcreting of the shaft and the installation of new thermal probes, the temperature distribution of the gas flux above the surface of the charge with limited gas flow along the furnace radius is not confirmed at the beginning of October (Fig. 5). This indicates that the distribution of the gas flux depends not only on the charging program but also on the state of the furnace lining.

CONCLUSIONS

We have established the influence of the blast parameters, including the natural-gas consumption and pulverized-coal consumption, on the temperature distribution of the peripheral gas flux and the gas flux above the surface of the charge.

Our findings regarding the influence of the gas dynamics on the gas temperature permit the identification of the factors affecting the temperature distribution of the gas with fluctuation in the furnace charge or the blast.

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