Development of heat-transfer circuits in the blast furnace

N A Spirin, Yu G Yaroshenko and V V Lavrov

Department of Thermophysics and IT in Metallurgy, Ural Federal University, 19 Mira Street, Yekaterinburg, 620002, Russia

E-mail: n.a.spirin@urfu.ru

Abstract. The development of heat-transfer circuits in the blast furnace as the technologies of blast-furnace smelting are improved are considered. It is shown that there are two zones of intense heat-transfer, and in modern conditions, when different kinds of iron ore are smelted, the use of combined blast with high parameters is a prerequisite for the stability of blast-furnace smelting operation and the smelting efficiency.

1. Introduction

Almost all physical and chemical processes occurring in the blast furnace are pyrometallurgical. Hence their development depends on the amount of heat, that is removed from the combustion zone, the distribution of temperature height wise and sections of blast furnaces. This relationship is complicated by the fact that the development of thermal processes that determine the level of temperature, in turn, are influenced by chemical processes changing during the smelting not only the composition and physical state of the charge components, but also their weight. Thus, heat- and mass-transfer are interrelated that determines the approach to the analysis of the blast-furnace smelting operation.

In the course of improvement of the blast-furnace smelting, development of the theory of heat transfer in the blast furnace and deepening of knowledge about the processes, significant clarifications have been made. The main outcome of the evolutionary development of the blast-furnace smelting operation is the reduction of coke consumption and increase of the smelting intensity.

2. Fundamentals of the theory of heat transfer in the blast furnace

The mathematical model, describing the thermal and physical-chemical phenomena of blast furnace smelting, was proposed by prof. B.I. Kitaev in 1944 [1]. The full description of the model is given in the monographs [2-5]. B.I. Kitaev considered the blast furnace as a countercurrent heat exchanger, where heat- and mass-transfer processes occur simultaneously. He found that the temperature distribution in the blast furnace is determined by the heat capacities of charge and gas flows, namely, by their ratio. The heat capacity of a flow of charge –W_m or gas – W_g (kJ/(hr °C) equals to the product of the charge flow rate –G_m, (kg/h) or gas – V_g (m^3/h) and the heat capacity of the substance in this flow – c_m (kJ/kg °C) or c_g (kJ/m^3°C), i.e.

$$W_m = G_m c_m \quad \text{or} \quad W_g = V_g c_g \qquad (1)$$

To take into account the thermal effects of exothermic or endothermic reactions B.I. Kitaev introduced the concept of "seeming" heat capacity of charge – cs, and proposed a formula for its calculation

$$c_s = c_f + (\pm c_{mas}). \tag{2}$$

The first summand in this expression – c_f is a physical heat capacity, and the second one – ($\pm c_s$) is a conditional heat capacity that takes into account the sinks and sources of heat during the heat- and mass-transfer processes of blast furnace smelting. If the value c_f in (2) is a volumetric heat capacity, than the value

$$\pm c_{mas} = \pm \Sigma q_{mas} / (v_m \times \Delta t_m), \tag{3}$$

where Σq_{mas} – the sum of heat-absorptions in the direct reduction processes, evaporation and decomposition of moisture and other processes requiring heat inputs (sign "+") for their development, and heat emissions in the process of indirect reduction, secondary oxidation and other processes accompanied by heat emission (sign "–"). Its value is determined by the quantity of the reacted substance and the thermal effect of the reaction;

v_m – volume of charge per 1 tonne of pig iron;

Δt_m – temperature range in which the heat absorptions or heat emissions are calculated.

The mass and volumetric "seeming" heat capacity can be used for the calculations of temperature fields in blast furnaces depending on the flow rates and thermo-physical properties of their constituent components. In the analysis of heat-transfer processes in the blast furnace the determining factor is the ratio of heat capacity of the charge flow – W_m to the heat capacity of a gas flow – Wg. Quantity m = W_m/W_g can take values m<1.0, m>1.0, and m = 1.0. Thus, the quantity m determines the difference in the nature of temperature fields along the column of charge.

Exploring the change in heat capacities of charge and gas flows in the blast furnace, Prof. B.I. Kitaev managed for the first time to determine the thermal and physical characteristics of the blast furnace which are as follows:

- heat capacity of a gas flow along the height of the blast furnace remains practically the same, since its decrease during the gas cooling is compensated by the increase in the amount of gas flow components of higher heat capacity, which are formed as a result of reduction of the iron-bearing charge material, evaporation and other possible processes;
- heat capacity of the charge flow has a more complicated nature. Changes of this characteristic are connected to the chemical aspect of the blast furnace process. In the upper parts of the furnace, where the physical processes of charge heating take place, this characteristic depend only on the temperature, and this dependence is smoothed by the action of a heat source during the indirect reduction. According to the estimates of B.I. Kitaev ratio W_m/W_g in this area of the furnace varies between 0.8...0.9. In the lower parts of the furnace, alongside with the physical processes of the charge melting and the melt superheating, direct reduction processes occur, which require less amount of heat. Such heat consumption causes the two- and threefold increase of seeming heat capacity of the charge. This process, as well as other endothermic processes lead to the fact that ratio W_m/W_g for the bottom of the furnace depending on the grade of the smelted pig iron can increase to 2.0...3.0. Change in the heat capacities of gas and charge flows along the height of the blast furnace is shown in Figure 1a. The lines, characterizing the heat capacities of gas and charge flows, indicate that for the top of the furnace $W_m<W_g$, i.e. m<1.0, and for the bottom at a considerable height $W_m>W_g$, i.e. m>1.0. Maximum of the development of direct reduction processes corresponds to the maximum of the heat consumption and, consequently, to the highest value of heat capacity of the charge flow. With further lowering of charge the development of the direct reduction processes weakens due to the decrease in non-reduced iron. As a result, the heat capacity of

the charge flow begins to decrease. Depending on the grade of pig iron the heat capacity of the charge flow at the level of tuyeres can be very close to the heat capacity of gases flow, and sometimes the condition may arise when $W_m<W_g$, that is indicated in Figure 1a as variations in the heat capacity of the charge flow.

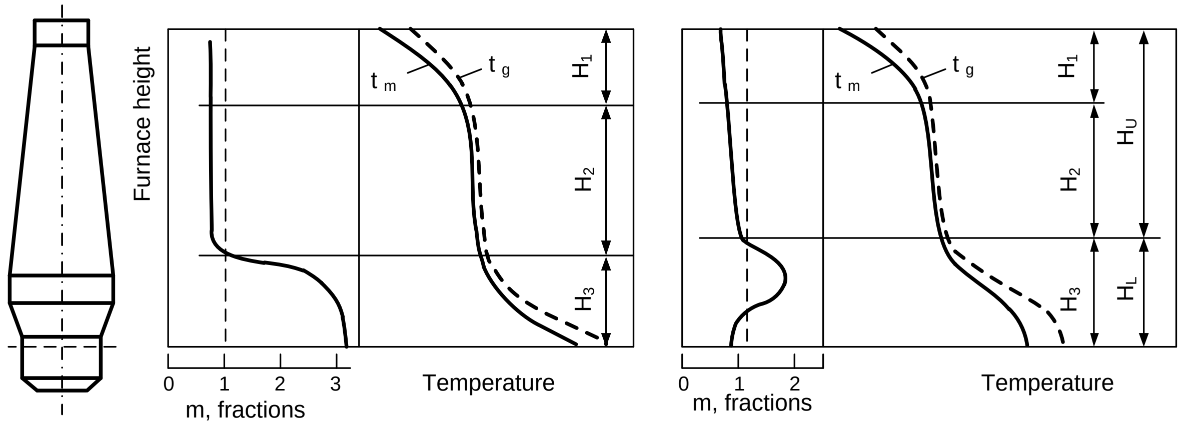


Figure 1. Heat-transfer circuit in the blast furnace: a – heat-transfer circuit of 1944; b – circuit of 1961; t_m, t_g – the temperature of charge and gas; m – ratio of the heat capacities of the charge and gas flows; H_1 – the upper stage of the heat-transfer; H_2 – thermal reserve zone r; H_3 – the lower stage of heat-transfer; H_U – the upper thermal zone; H_L – the lower thermal zone.

Analysis of changes in the heat capacities of charge and gas flows helped to conclude that the heat-transfer in the blast furnace follows the circuits shifted along the height and different in ratios of heat capacities of flows. Laws of heat-transfer in the counter-flow heat exchangers allowed the temperature distribution along the height of the blast furnace to be presented in a generalized form in Figure 1b. As appears from the analysis of temperature fields and flows of gas:

- in the upper part of the blast furnace (the upper stage of heat-transfer –H_1) the heat capacity of the charge flow is less than of the gas flow, i.e. $W_m<W_g$. Under these conditions the gas flow always contains more heat than the charge can absorb. The excess heat is carried away through the furnace mouth, and the heating of the charge to the temperature of gas practically occurs at a depth of 5-8 m below the charge level;
- in the lower parts of the furnace (lower stage of heat-transfer – H_3) heat capacity of the charge flow is more than the heat capacity of the gas flow, namely $W_m>W_g$. With this ratio the charge cannot be heated to the temperature of the combustion zones. After the heat-transfer the charge will have a temperature lower than the initial temperature of gases. Thus, within the lower stage of heat-transfer the temperature differential between the gas and the charge, as the charge being lowered, increases and reaches the maximum in the combustion zones. This area of heat-transfer is characterized by high values of heat-transfer coefficients, significantly developed surface of heat-transfer due to the melting of iron ore and slag formation and, that is very important, by the development of endothermic reduction processes of CO_2 with coke carbon. These conditions lead to the fact that the relatively small height of the column of charge materials is sufficient for the heat energy exchange between the gas and charge. At the exit from the lower stage of heat-transfer – H_3, the temperatures of the gas and charge flows become practically the same;
- in the middle part of the blast furnace (moderate temperature zone – H_2) the heat capacity of the gas and charge flows converge $W_m \approx W_g$. The charge is heated at the exit from the upper stage of heat-transfer almost to the temperature of gas leaving the lower stage of heat-transfer. But due to lack of heat reserve in the gas flow the heat-transfer rate decreases to almost zero values.

The full description of the model is given in monographs [2-6]. Using the analysis results of changes in the heat capacities of charge and gas flows along the height of the furnace, B.I. Kitaev formulated the basic provisions of the theory of heat-transfer in the blast furnace, which are as follows [1, 2]:

- The gas-material heat-transfer rate is carried out in two stages of heat-transfer: in the upper and lower stages. The stages of heat-transfer are separated by the thermal reserve zone, where the temperature gradient along the height reaches a minimum value.
- Thermal performance of each stage of heat-transfer is notable for independence (autonomy) and is characterized by a significant difference in ratios of heat capacities of charge W_m and gas flows W_g. The thermal reserve zone, separating the active heat-transfer zones, is characterized by the ratio of heat capacities of flows $m = W_m/W_g$ close to 1. The upper stage of heat-transfer has $W_m<W_g$, i.e. $m<1.0$, and the lower stage $W_m>W_g$, i.e. $m>1.0$.
- Heat-transfer in the blast furnace is completed which is proved by the existence of the thermal reserve zone. In this zone the heat capacities of the gas and charge flows converge so that $W_m \approx W_g$, $m \approx 1.3$

The nature of changes in the gas and charge temperatures, the ratio of their heat-capacities along the height of the furnace are presented in Figure 1a. Thus, along the height of the blast furnace at a regular performance the typical S-shaped temperature distribution is observed.

3. Development of heat-transfer circuit in the blast furnace

The experiments on the operating furnaces in subsequent years showed that the height of the lower stage of heat-transfer is actually greater than the values obtained from the calculations made according to the circuit in Figure 1a. The accumulated data on heat-transfer in the lower stage created the conditions for the further development of heat-transfer circuit. B.I. Kitaev, B.L. Lazarev, Yu.G. Yaroshenko [4-7] expanded the heat-transfer circuit, according to which the upper stage of heat-transfer and the thermal reserve zone remained unchanged, but another character of change in the ratio of heat capacities along the height of the lower stage of heat-transfer was accepted. With approach to the level of blast tuyeres the ratio, like in the old circuit, initially increased, but as the intensity of the direct reduction reaction decreased this ratio became less than one. At the same time the temperature curves of charge and gas in the lower stage of heat-transfer got the typical downward bend of temperature gradient. The revised circuit of heat-transfer along the height of the blast furnace shown in Figure 1b differs from the circuit in Figure 1a due to the division of the lower stage of heat-transfer into two parts: for the upper stage $W_m>W_g$, and the lower stage $W_m<W_g$, that is conditioned by the end of the process of direct reduction of iron oxides to the lower level and, consequently, the overall heat absorption of the charge is substantially reduced.

The research of blast furnaces performance in the next decades shows that the temperature field along the height of blast furnaces undergoes a significant deformation. The essence of this tendency lies in the presence of several local thermal reserve zones in the temperature curves along the furnace height. N.N. Babarykin and F.A. Yushin were the first to note it while considering the temperature field obtained by the method of vertical sounding of MMK blast furnaces. A series of measurements during smelting of different iron ore in some cases showed the presence of two zones of hardly varying temperature along the stack height (Figure 2) [8].

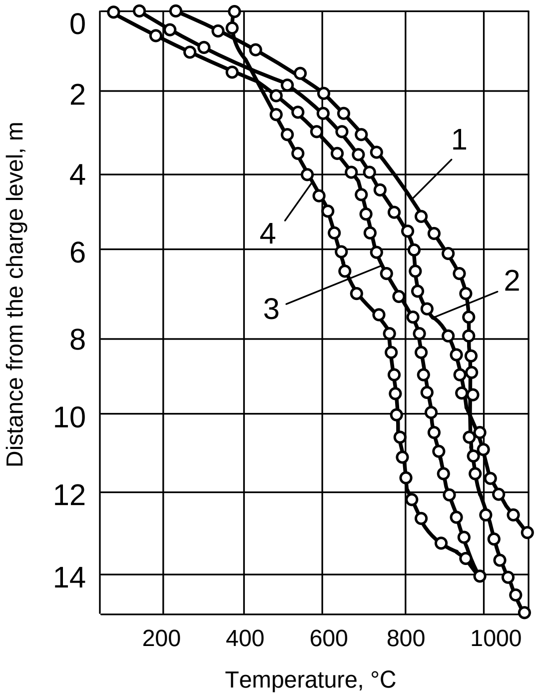


Figure 2. Change of the gas temperature along the blast furnace height during the smelting of lime fluxed pellets (1), dolomite fluxed pellets (2), non-fluxed pellets (3) and sinter (4).

Summarizing the experimental data on thermal and reduction performance of blast furnaces, prof. N.N. Babarykin [8] proposed the heat-transfer circuit given in Figure 3. According to this circuit the observed in the experiments two thermal reserve zones along the stack are formed as a result of chemical reactions with negative thermal effects. Formation of the upper section is conditioned by the effect of endothermic reactions of magnetite reduction with carbon monoxide, and the formation of the lower section is connected with the heat absorption during a substantial development of reaction of coke carbon gasification with carbon dioxide.

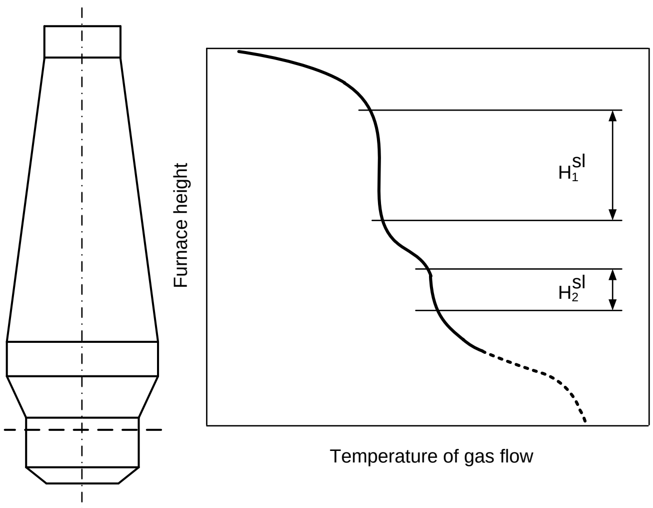


Figure 3. Scheme of temperatures distribution along the furnace height according to N.N. Babarykin: H_1^{sl}, H_2^{sl}– upper and lower sections of slowed heat-transfer.

The published data on mathematical modeling of heat- and mass-transfer in the blast furnaces show that two thermal reserve zones do not always appear during the formation of temperature fields in the furnace shaft [6]. This is understandable, because the simulation results largely depend on the adopted coefficients values of the model settings and, in particular, on the kinetic characteristics of iron ore raw material and heat-transfer coefficients. One of the key parameters in the calculations is the heat-transfer coefficient. Its values in the earlier calculations determined the low temperature difference of charge and gas [1-4]. According to the calculations of A.N. Ramma at the underestimated values of the heat-transfer coefficient this difference reaches 50-150 °C [9].

In this connection the results of simulation of the joint development of heat-transfer and reduction processes along the stack height, performed by B.I. Kitaev and his disciples, are of specific interest. Along with that the assumption was made about the stepwise nature of the iron oxides reduction. In Figure 4 and 5 the simulation results relating to the operating conditions of blast furnace No. 3 with volume 3000 m^3 at West Siberian Metal Plant are presented [10].

The overall picture of heat-transfer and reduction processes shown in Figure 4 is the most complicated case of manifestation of their relationship in the upper part of the charge, when the charge flow is overheated by the opposing gas flow. This area is characterized by the relatively small temperature difference between the gas and the charge. Therefore, this area, as well as the adjacent horizons, differ in the relatively low heat flow from the heating medium to the heated material and form a thermal reserve zone in the upper part of the blast furnace. The temperature level of this zone varies in the range 700-760 °C.

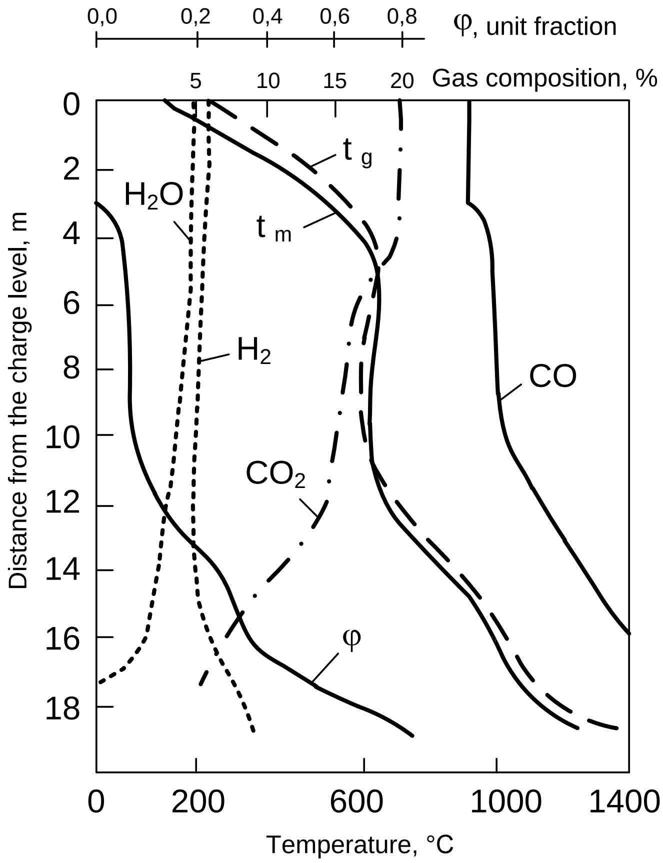


Figure 4. Change in the basic parameters of reduction along the height of the blast furnace shaft in the presence of local overheating of charge relative to gas: φ – the degree of materials reduction; q_g – consumption of the gasified coke carbon.

In Figure 5 the results of mathematical modelling of other operating conditions are presented, when the charge overheating relative to gas does not occur. If there is no overheating of charge compared to gas in the upper layers of the blast furnace shaft, the vertical and low-inclined sections of the temperature curves also form a thermal reserve zone. The reduction processes in this area are resented by underdeveloped reactions of the second stage of reduction. Below the upper thermal reserve zone the heat flow from gas to charge increases, the charge temperature goes up rather rapidly.

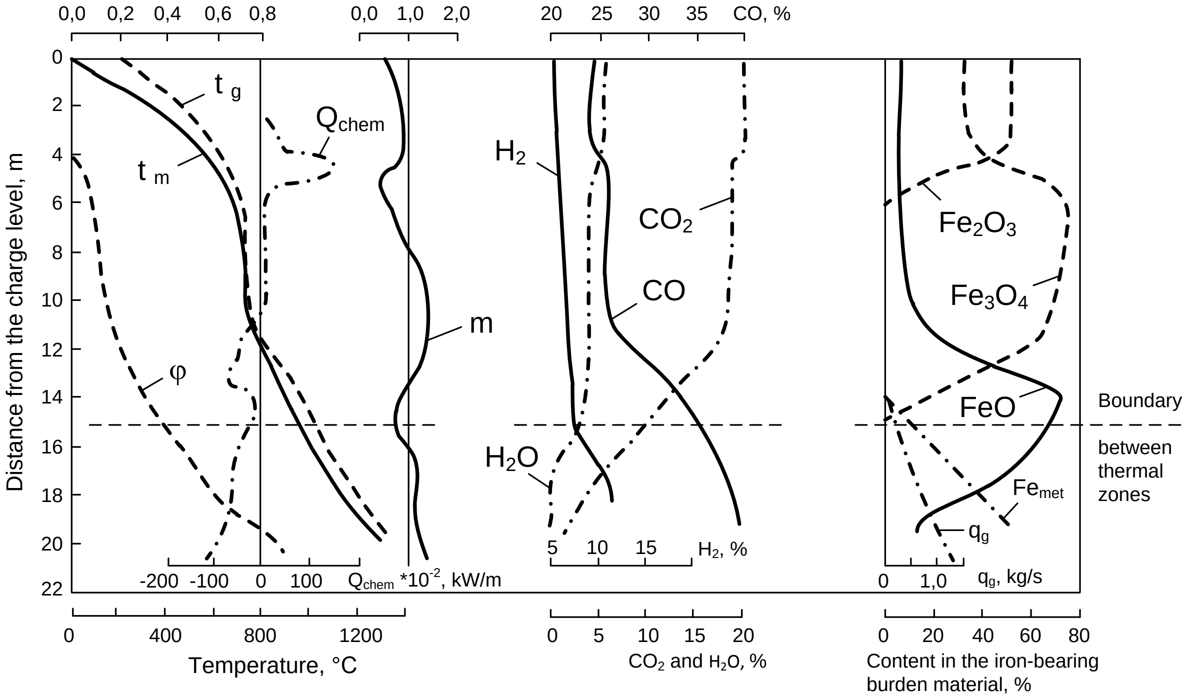


Figure 5. The simulation results of the joint development of heat-transfer and reduction processes in the absence of local overheating of charge relative to gas.

The height of the second (lower) thermal reserve zone depends on the ratio of thermal effects of exo- and endothermic reactions at the final stage of iron oxides reduction. However, a much greater role in the heat consumption in this part of the shaft height begins to play the reaction of coke carbide gasification, which is characterized by high values of thermal effect.

The features of heat-transfer development in the shaft of the blast furnace obtained during the modelling show that the difference between the gas and charge temperatures along the heating medium motion can repeatedly decrease and increase, reflecting a complicated process of mutual influence of heat-transfer and reduction.

4. Modern understanding of heat-transfer circuit in the blast furnace

Summarizing the experimental and theoretical studies of the processes in the furnace shaft and the previously obtained data on the operation of the lower part of the blast furnace, B.I. Kitaev with his followers offered a refined circuit of heat-transfer along the furnace height [5; 10] given in Figure 6, allowing the development of heat-transfer in the blast furnace to be shown for the modern technology of iron pig production.

Specific modes of blast-furnace smelting might differ in horizons of the selected circuits in some areas of heat-transfer and reduction, as well as the particular temperatures in these areas.

Two thermal reserve zones bring up the question concerning the earlier established concept of separation of blast furnace along the height into thermal zones. Therefore, we should note the following point.

The upper thermal reserve zone according to the results of mathematical modeling is characterized by the low heat-transfer rate and low-speed reduction reactions. Thus, the upper part of the thermal reserve zone is the reserve height providing improvement of thermal and reduction operation of furnace.

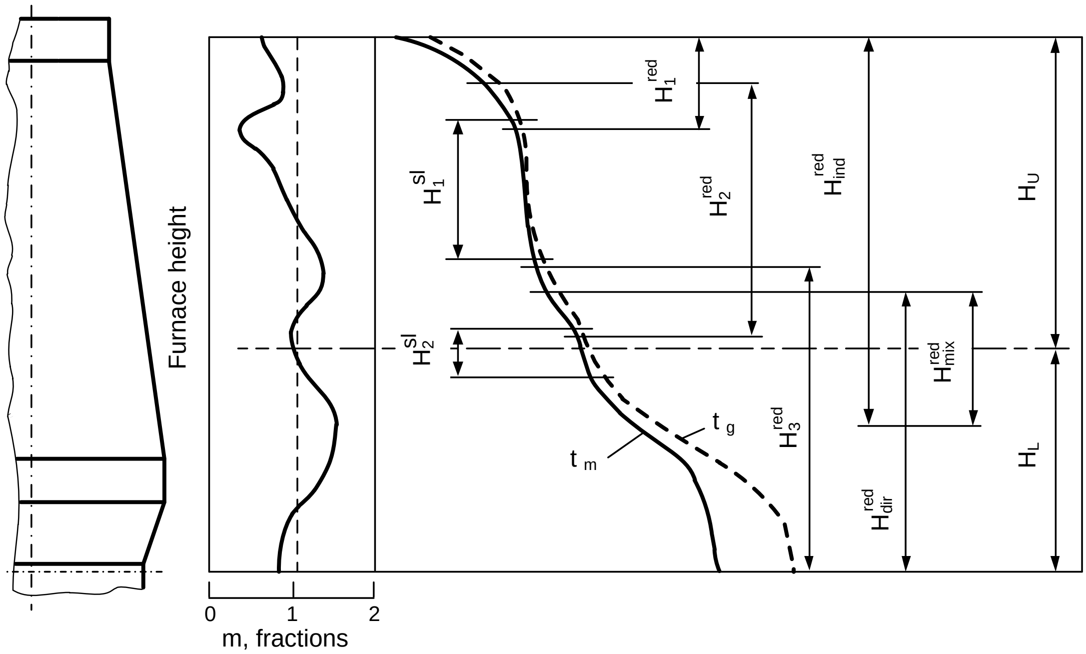


Figure 6. Heat-transfer circuit along the blast furnace height in modern technology of blast furnace smelting: H_1^{sl}, H_2^{sl} – the upper and lower parts of thermal reserve zone; $H_1^{red}, H_2^{red}, H_3^{red}$ – reduction zones of hematite, magnetite and wustite; $H_{ind}^{red}, H_{dir}^{red}, H_{mix}^{red}$ – zones of indirect, direct and mixed reduction; H_U, H_L – the upper and lower heat zones.

The lower part of the thermal reserve zone is characterized by the fact that at low thermal flows from gas to charge the rates of chemical reactions are quite high. Intensification of reduction in this area of the shaft will cause acceleration of coke carbon gasification with carbon dioxide and water vapor, which in turn will lead to the increased coke consumption. On this basis, it can be argued that the lower part of the thermal reserve zone as a reserve for improvement of thermal and reduction processes in the blast furnace should not be used.

In this regard, for the study and evaluation of the thermal state of the blast furnace as a control object it is reasonable to continue division into two thermal zones, the upper and lower one. The interface between them is located in the upper area of the mixed reduction, between the level of beginning of coke carbon gasification and the horizon, below which the iron oxides are reduced directly.

During intensification of the smelting processes due to the use of combined blast there is a change in the heat-transfer processes. On the basis of analytical calculations [17; 18] it is concluded that as the blast is enriched with oxygen and the theoretical combustion temperature goes up, the ratio of heat capacities of gas and charge flows – m in the upper stage of heat transfer increases. When approaching the critical limit of oxygen enrichment the degeneracy of the upper stage of heat-transfer is possible (Figure 7).

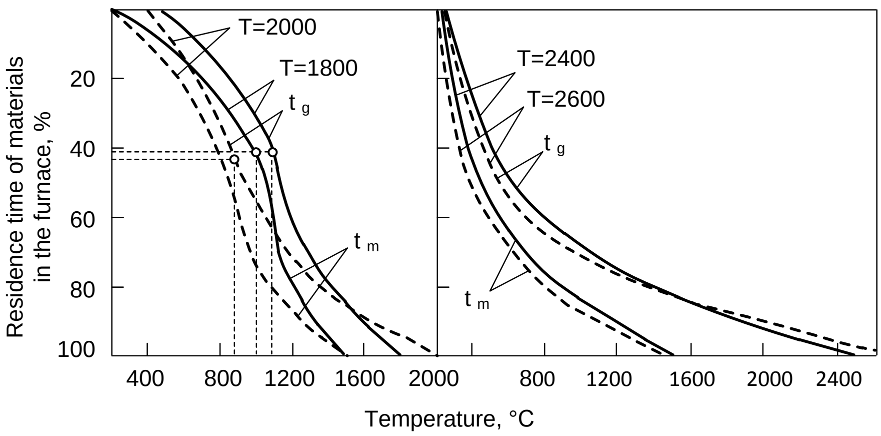
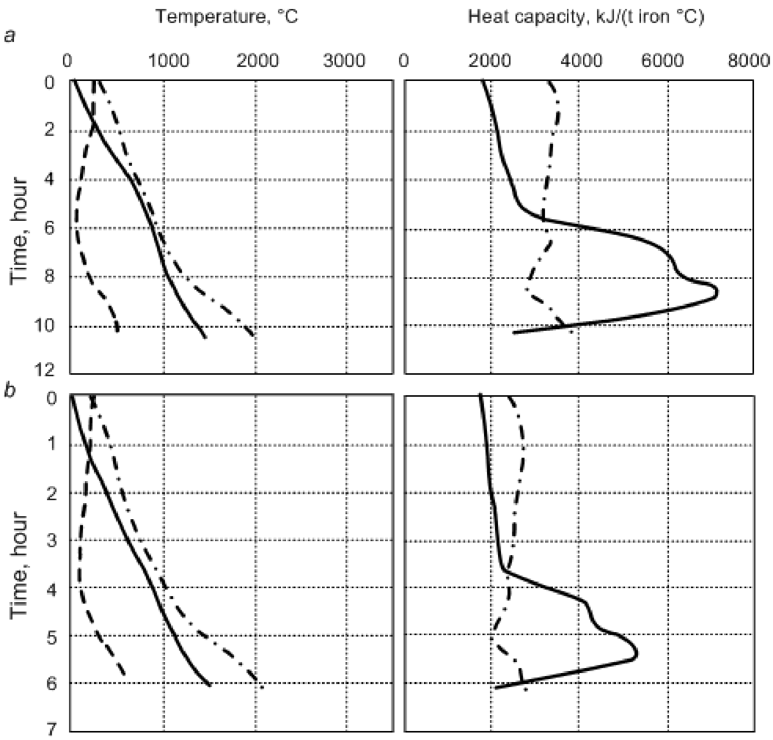


Figure 7. Change in the time and temperature of the materials and gases while the materials remain in the blast furnace at different values of the initial gas temperature at tuyeres (blast oxygen enrichment) according to the data [17].

However, degeneracy of the upper stage of heat-transfer during deep oxygen enrichment is possible only theoretically without taking into consideration the intrinsic properties of the blast furnace smelting operation and effect of feedback. In practice this circuit cannot be realized. In this case, the area of indirect reduction if substantially reduced, the degree of direct reduction inevitably increases, for this purpose additional carbon is required. As a result coke consumption or injected fuel should be increased, that will lead to the recovery of two-stage heat-transfer circuit. This provision is widely confirmed by both experimental and theoretical studies [12-18]. Thus, the concept of “autonomy of the upper and lower heat-transfer zones” should not be understood literally, they interact through the degree of direct reduction.

In Figure 8 (a, b, c) I.G. Tovarovskiy’s distribution charts of temperatures and heat capacities of materials and gases [11] are provided for three cases:



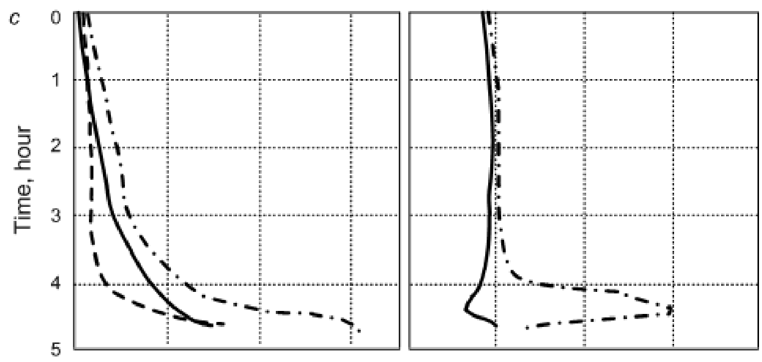


Figure 8. Distribution of temperatures and heat capacities of gas and charge flows while the materials remain in the blast furnace:

· — · — · — · —temperature and heat capacity of the gas flow;

——— temperature and heat capacity of the charge flow;

– – – – temperature difference between the gas and the charge

a – general mode with injection of atmospheric blast at temperature 1100 °C and natural gas (100 m^3/tonne) with output to 1.5 tonne/(m^3d);

b – intensive mode with injection of oxygen-enriched blast up to 40% at temperature 1300 °C and natural gas (180 m^3/tonne) with output 2.7 tonne/(m^3d);

c – the same as b, but without natural gas and output – 3 tonne/(m^3d).

In (a) there is a conventional two-stage heat-transfer, in which the heat capacity of gases flow in the shaft (upper stage) is greater than the heat capacity of materials flow, and during the lowering of charge and heating of materials the temperature difference between the gases and materials decreases to some minimum reaching m=1, after which m>1.0 and the temperature difference increases.

Case (*b*) is characterized by the fact that due to the increase in the quantity of gases the heat-transfer rate in the upper area decreases and the temperature difference between the gas and the charge on the boundary of heat-transfer zones goes up along with the transfer of thermal performance to the bottom of the furnace.

In (c) the limiting conditions for heat-transfer are observed, in which due to the small amount of gas per unit of charge the shaft "is turning cold", the temperature difference between gases and materials goes up and changes little during the lowering of materials, and m≈1 along the shaft height. "Degeneracy" of the upper stage of heat transfer and localization of all processes in the lower stage takes place. This case demonstrates the typical process instability and does not occur in actual practice.

5. Conclusions

Summarizing and analysis of experimental and theoretical studies showed that a two-stage heat-transfer circuit in the modern conditions of the blast furnace operation during smelting of various types of iron ore, use of the combined blast of high parameters, significant reduction of coke consumption and increase of the smelting rate, is a prerequisite for stability of the blast furnace operation and smelting efficacy. Any changes in the technology of modern blast furnace smelting should not change this circuit. The upper and lower stages of heat-transfer are connected with each other by the direct reduction processes, which eliminates the full autonomy of these stages of heat-transfer.

6. Acknowledgements

IOP Conf. Series: Materials Science and Engineering **150** (2016) 012022 doi:10.1088/1757-899X/150/1/012022

The work was supported by the Government of the Russian Federation, Act No. 211, contract No. 02.A03.21.0006.

7. References

[1] Kitaev B I 1944 *Steel* 7–8
[2] Kitaev B I *Heat-transfer in the Shaft Furnace* (Sverdlovsk-Moscow: Metallurgizdat) p 152
[3] Kitaev B I, Yaroshenko Y G and Suchkov V D 1967 *Heat Exchange in Shaft Furnaces* (London: PERGAMON PRESS) p 299
[4] Kitaev B I et al 1966 *Heat-transfer in the Blast Furnace* (M.: Metallurgiya) p 355
[5] Kitaev B I et al 1978 *Thermal Engineering of Blast Furnace Smelting Operation* (M.: Metallurgiya) p 248
[6] Dmitriev A N 2011 *Mathematical Modeling of the Blast Furnace Process* (Ekaterinburg: Ural Branch of RAS) p 162
[7] Ovchinnikov Yu N et al 1989 *Non-stationary Processes and Improvement of the Efficiency of Blast Furnace Smelting* (Chelyabinsk: Metallurgiya) p 120
[8] Babarykin N N 1981 *Steel* **3** 5–9
[9] Ramm A N 1980 *Modern Blast Furnace Process* (M.: Metallurgiya) p 304
[10] Spirin N A 1995 *Heat-transfer and Increase of Blast Furnace Smelting Efficacy* (Ekaterinburg: USTU) p 243
[11] Tovarovsky I G 2015 *Study of Processes and Development of Technology of Blast Furnace Smelting* (Dnepropetrovsk: Porogi) p 913
[12] Ando R et al 1972 *Ferrous metallurgy: Express-information* **33** (146) 1–30
[13] Spirin N A et al 2011 *Model of Decision Support System in the Process Control System of Blast Furnace Smelting* (Ekaterinburg: UrFU) p 462
[14] Junichiro Yagi 2012 *6th Int. Con. on Science and Technology of Iron Making – ICSTI* (Rio de Janeiro, RJ, Brazil) pp 1660–74
[15] Jian Xu, Sheng-li Wu et al 2012 *Tech. Contrib. to the 6th Int. Cong.on Science and Technology of Ironmaking – ICSTI* (Rio de Janeiro, RJ, Brazil) pp 414–424
[16] Hatano M, Misaka Y, Matoba Y and Otsuka K 1982 *Trans. Iron and Steel Inst. Japan* **22** (7) 524–533
[17] Spirin N et al 2014 *Trans. on Ecology and the Environment* (Ekaterinburg: UrFU) **190** (1) pp 467–478
[18] Bokovikov B A et al 2015 AISTech 2015 *Iron and Steel Technology Conf. and 7th Int. Conf. on Science and Technology of Ironmaking, ICSTI 2015* (Cleveland) **1** pp 237–244