Mathematical model and software for control of commissioning blast furnace

N A Spirin, O P Onorin, K A Shchipanov and V V Lavrov

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

E-mail: spirin@urfu.ru

Abstract. Blowing-in is a starting period of blast furnace operation after construction or major repair. The current approximation methods of blowing-in burden analysis are based on blowing-in practice of previously commissioned blast furnaces. This area is theoretically underexplored; there are no common scientifically based methods for selection of the burden composition and blast parameters. The purpose of this paper is development and scientific substantiation of the methods for selection of the burden composition and blast parameters in the blast furnace during the blowing-in period. Research methods are based on physical regularities of main processes running in the blast furnace, system analysis, and application of modern principles for development and construction of mathematical models, algorithms and software designed for automated control of complex production processes in metallurgy. As consequence of the research made by the authors the following results have been achieved: 1. A set of mathematical models for analysis of burden arrangement throughout the height of the blast furnace and for selection of optimal blast and gas dynamic parameters has been developed. 2. General principles for selection of the blowing-in burden composition and blast and gas dynamic parameters have been set up. 3. The software for the engineering and process staff of the blast furnace has been developed and introduced in the industry.

1. Introduction

Blast furnace blowing-in and subsequent blowing period are critical operations and correct execution of these operations has an impact on normal performance of the blast furnace, its service life, quantity and duration of mid-life repairs. The analysis of literature data related to blast-furnace production has shown that there are approximation methods of blowing-in burden analysis based on blowing-in practice of previously commissioned blast furnaces [1–7]. Modelling of the one-dimensional non-steady state of temperature fields for blast furnace blowing-in was performed by foreign researchers [8–10]. However, this area is theoretically underexplored; there are no common scientifically based methods for selection of the burden composition and blast parameters.

In case of forced blowing-in (with controlled slag formation and reduction) the first portions of slag-forming and iron-ore materials are located in the furnace stack. In this case, there is no necessity to gradually increase the ore load [4–5, 7]. The structure of the mathematical model for calculation of blowing-in burden during forced blowing-in is shown in Figure1. The burden charged in the blast furnace is divided into three parts (zero burden, first burden, second burden).

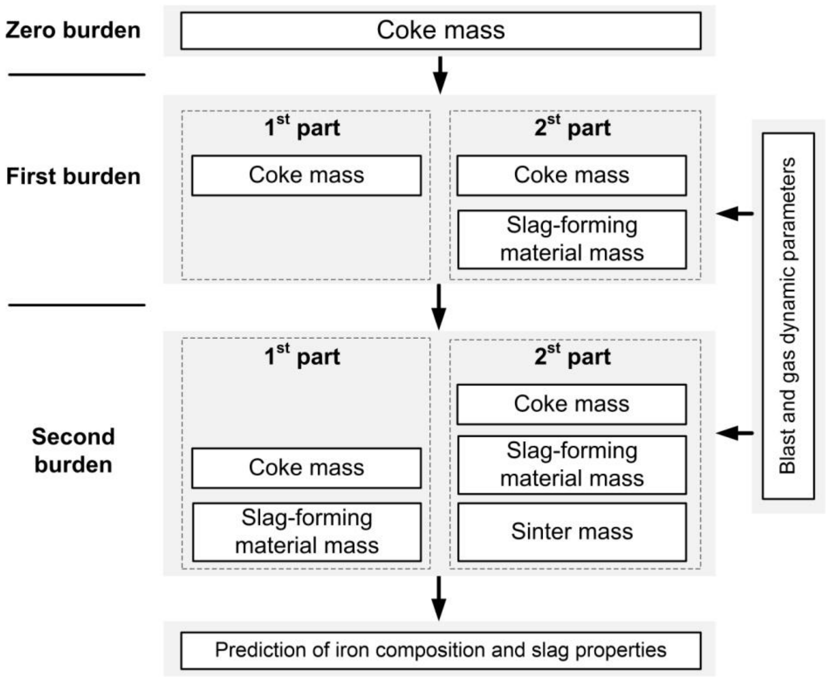

Figure 1. Structure of mathematical model for burden calculation during forced blowing-in.

The "zero burden" which consists only of coke does not take part in the combustion process and fulfils the role of drainage coke packing. The volume of the zero burden includes the following:

- well (hearth volume determined by the height of the fixed bed material);
- hearth volume from the iron tap-hole level to the blast tuyere level;
- coke volume in the cone of fixed materials from the blast tuyere level (dead man coke).

The mathematical model structure of the "first burden" analysis is shown in Figure 2.

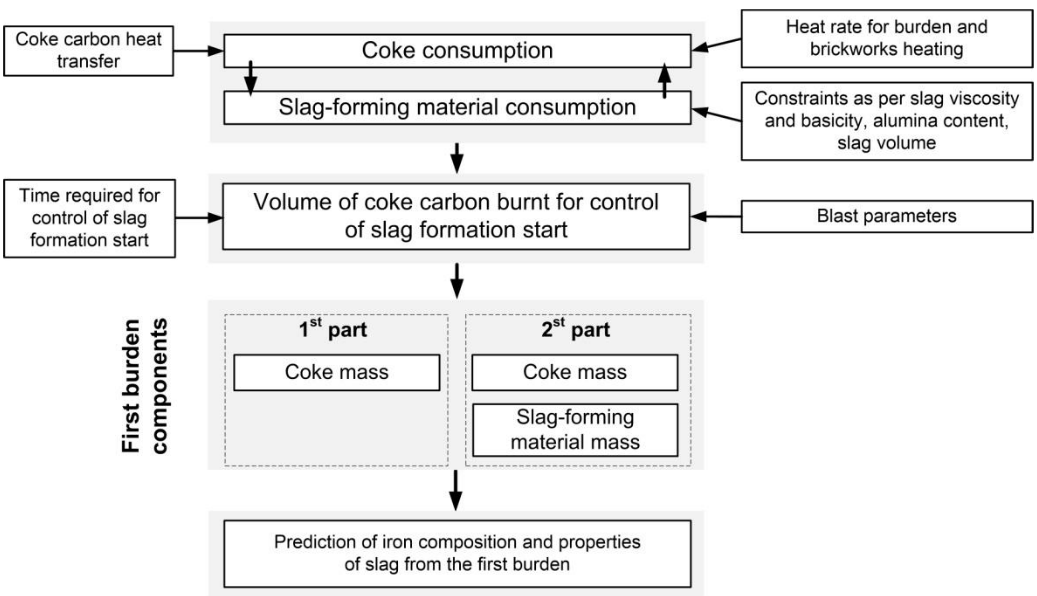

Figure 2. Structure of mathematical model for "first burden" calculation.

The first burden is divided into two parts; the first part consists of coke and the second part consists of coke and slag-forming materials. The sequence of calculations for determining parameters of the first burden is as follows:

- to determine the required coke consumption for heating of burden and refractory brickworks up to the operating temperatures on the basis of heat balance, i.e. the quantity of heat from burning coke of the first burden shall be sufficient for heating of refractory brickworks and materials of this burden up to the operating temperatures typical of the lower step of heat transfer;
- to calculate consumptions of slag-forming materials on the basis of the assigned slag composition (CaO/SiO_2, Al_2O_3) and assigned slag viscosity at 1400°C and 1500°C; the slag viscosity calculation is based on mathematical treatment of known slag diagrams at these temperatures;
- due to addition of slag-forming materials into the burden some additional coke consumption is required for heating and smelting of these materials; since the coke consumption changes, it is necessary to correct the burden composition as at the increased coke consumption there are changes in the slag composition and properties. The iterative procedure for calculation of coke and slag-forming material consumption is shown in Figure 3;
- to determine the location of the first burden along the furnace height; addition of slag-forming materials into the first part of the first burden is not provided; slag-forming materials coming from coke ash during combustion of first burden coke are distributed in fractional voids of the coke packing, they do not form free-running slag.

This method of furnace blowing-in means operation of the furnace hearth without slag, which gives an opportunity to remove hot gases through the pipes embedded in iron tap-holes. Otherwise, in case of early slag formation the pipes will be inevitably filled up with slag and gas flow in the hearth bottom will stop, which will not allow heating of the hearth bottom to the operating temperatures providing normal production of the first portions of molten slag and iron. Industrial blowing-in of the blast furnaces using the technology of the delayed slag formation shows that the furnace operation time before slag will appear in the hearth shall be more than 6 hours and reach up to 10 hours without any risk of significant breaking in gas dynamic properties of the burden column [4, 5]. The speed of burden movement in the furnace and arrival time of slag-forming materials to the tuyeres are determined by flow rates of blast, natural gas and oxygen as well as by blast humidity. After changes in these parameters are set in the course of blowing-in, it is necessary to calculate the coke quantity required for timing of the slag formation start.

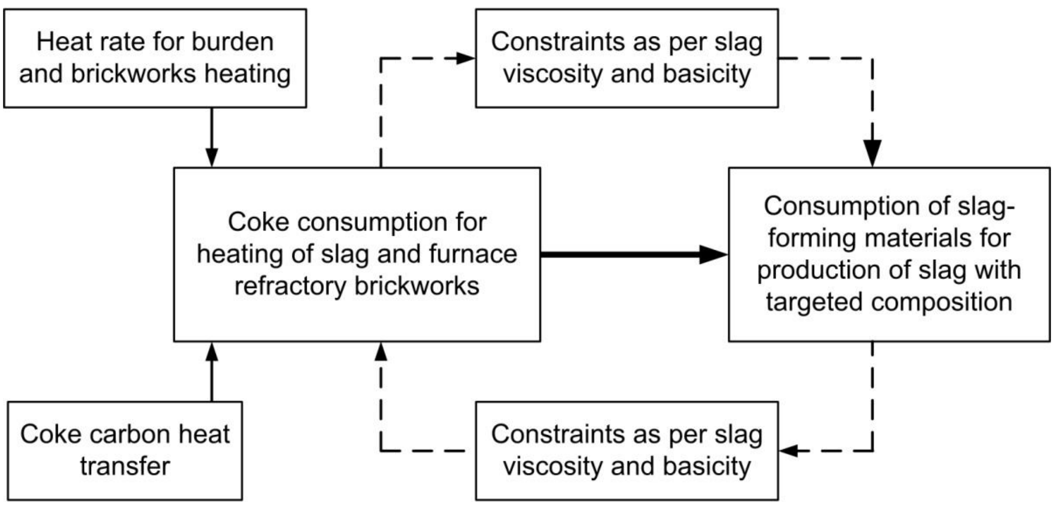

Figure 3. Iterative procedure for calculation coke and slag-forming material consumption.

The structure of the mathematical model for the “second burden” analysis is shown in Figure 4.

The same as the first burden, the second burden is divided in two parts. The first part consists of coke and slag-forming materials and the second part consists of coke, slag-forming and iron-ore materials.

In order to determine the consumption of burden components in total for the second burden, A.N. Ramm’s calculation method [11] is applied. This method is used to determine the specific consumption of iron-ore materials and coke for one ton of iron as well as the average value of the ore load. Consumption of slag-forming materials and flux is calculated in the same way as for the first burden. The difference is that the presence of iron-ore materials is considered in the second part of the second burden. Arrangement of the first portions of ore materials of the second burden throughout the furnace height is of great importance. This is related to the necessity of good heating and complete reduction of iron oxides in the ore material.

In case iron-ore materials are located at a low height, it is possible that high-iron slag will go to the furnace bottom, which will result in chilling of the furnace bottom, inappropriate filtration of the melts in the hearth and problems with molten products in the course of tapping. This distance is related to the residence time of burden in the furnace. In this respect the permissible time of iron-ore material arrival to the blast tuyeres is used as a model setting and at the assigned rate of furnace blowing-in the level of ore material in the blowing-in burden is determined. The experience of blast furnace blowing-in gives evidence that the value of the theoretical flame temperature at the initial period of furnace blowing-in shall be as low as possible. This is explained by the fact that at this stage of blowing-in there are no heat consumers (ore and slag-forming components) in the furnace hearth. The permissible theoretical flame temperature is maintained by blast parameters, particularly by blast humidity.

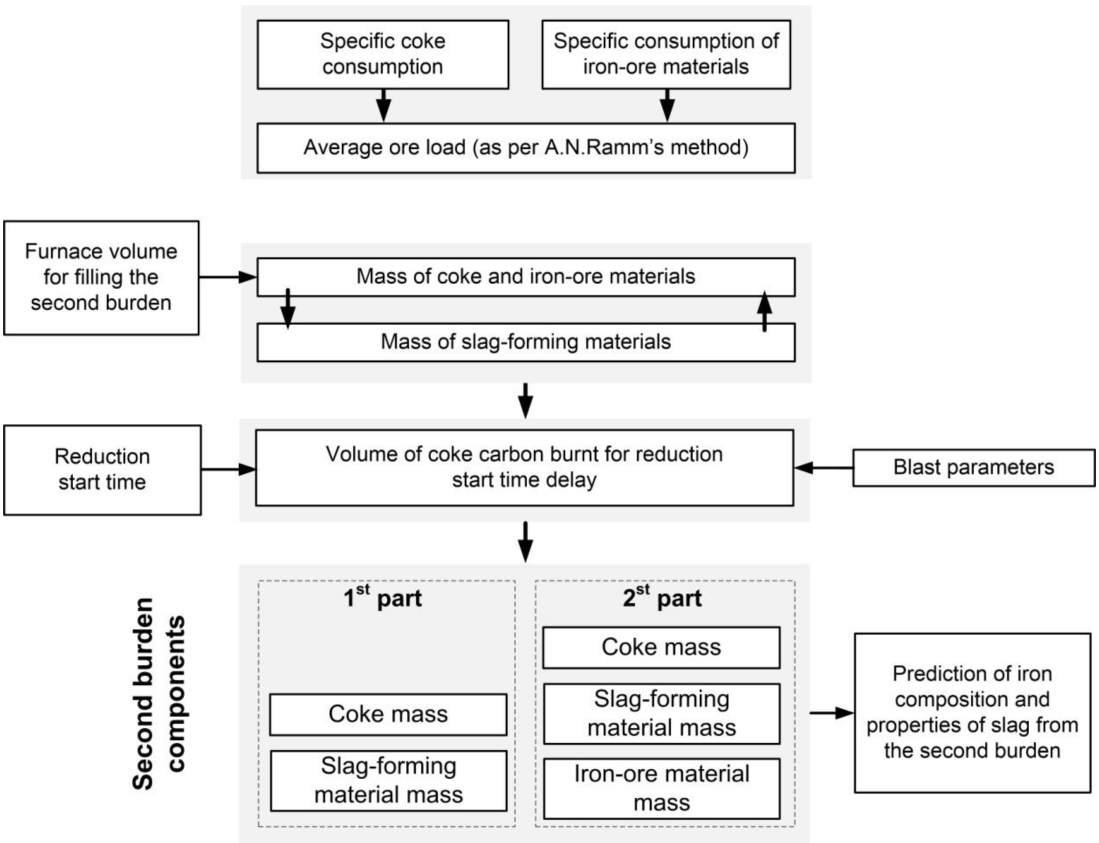

Figure 4. Structure of mathematical model for “second burden” calculation.

The predicted content of sulphur in cast iron is calculated as per sulphur balance which is made up of all sulphur-containing components of burden, slag and iron [12]. The coefficient of sulphur distribution between iron and slag LS is determined by many factors, particularly by slag temperature, activity of CaO in slag, CO partial pressure in the area of iron direct reduction and others.

Modelling of combustion zone parameters. With the small blast flow rate set at the initial stage the development of combustion zones is of the utmost importance as the small blast flow rate causes a small development of combustion zones, poor heating of the axial part of the burden column and leads to a peripheral gas flow with low utilization of the thermal and reducing capacity of the gas flow. The combustion zone performance analysis based on the use of empirical dependences makes it possible to evaluate the length of the raceway and oxidizing zones, the area of the oxidizing zones and their changes at varying smelting conditions. The experience of furnace blowing-in gives evidence that the value of the theoretical flame temperature at the initial period of furnace blowing-in shall be as low as possible – about 1850-1900°C. This is explained by the fact that during blowing-in there are no heat consumers (ore and slag-forming components) in the furnace hearth, and due to extreme heating of the furnace bottom during coke combustion hot suspensions of burden are inevitable at the tuyeres.

Modelling of gas dynamic melting conditions. It should be noted that the blowing-in burden layer is characterized by the decreased bulk density due to the large consumption of coke in burden and, therefore, burden suspension occurs at a lower differential than it happens in the normal melting conditions. The degree of gas utilization (DU) for burden balancing is taken as a criterion of burden layer stability in the furnace exposed to the gas flow. The limit differential pressure over which burden suspension in the furnace occurs is reached at the critical degree of gas utilization (DUcrit.) [12].

Optimization model of blowing-in burden. It is required to determine the burden composition and select the blast parameters on the basis of the assigned slag basicity (CaO/SiO_2). In this case the process constraints for heat, blast, gas dynamic and slag conditions shall be taken into account. These constraints are as follows:

- slag viscosity at 1400°C and 1500°C, poise;
- Al_2O_3 content in slag, %;
- slag yield, t/t;
- sulphur content in cast iron, %;
- silicon content in cast iron, %;
- theoretical flame temperature t at the tuyeres, °C;
- degree of gas utilization for burden balancing, %.

The task description for selection of the optimal burden composition, blast and gas dynamic parameters during furnace blowing-in as well as the sequence of optimization task solution are shown in Figure 5.

The characteristic feature of finding a solution for complex optimization tasks in mathematical programming is that there can be cases when the constraints put on heat, gas dynamic and slag conditions of blast furnace operation during blowing-in are contradictory, i.e. there is no region of feasibility. In this regard the solution algorithm provides a stage of task solution analysis. If there is no task solution and the conditions are contradictory, it is necessary to use the stage of correction, i.e. evaluate reasonability for the use of burden material data, constraints, reliability of the input data, etc.

The main functional capabilities of the software developed by the authors:

- maintenance of directories (blast furnace design characteristics; parameters of previous blowing-ins, properties of slag-forming materials, iron-ore materials and coke, etc.);
- calculation of blowing-in burden composition and iron / slag properties with the consumption of slag-forming materials and fluxes, blast parameters assigned by the user;
- calculation of the optimal composition of blowing-in burden and selection of blast parameters with account of the constraints for heat, slag and gas dynamic conditions and quality of the produced cast iron at any assigned combinations of input parameters;

- diagnostics and presentation of the calculation results in tables and graphics, storage in the database.

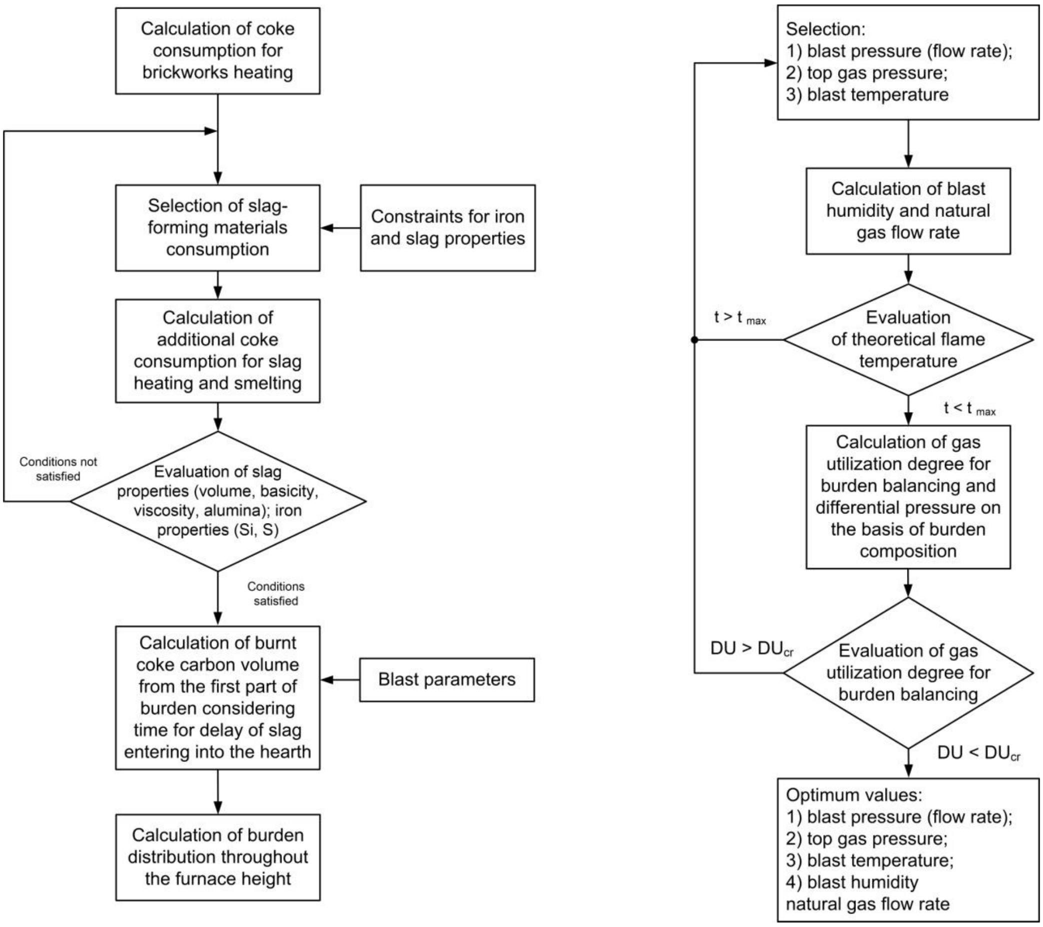

Figure 5. Task solution diagram for selection of the optimal composition of the first burden, blast and gas dynamic parameters.

The analysis of the calculation results has made it possible to set up general principles for selection of the blowing-in burden composition and blast and gas dynamics parameters:

- basicity of final slag as per CaO/SiO_2 ratio changes within the range of 0.9–1.0 depending on the silicon content in iron;
- average ore load without fluxes and slag-forming materials is 0.6–0.7 t/t;
- ore load in the iron-ore part of the blowing-in burden (the second part of the second burden) is 2.4–3.0 t/t;
- arrangement of blowing-in burden materials shall be in accordance with the following principles:
- slag-forming materials shall be charged at the height of minimum 7.0 m from the blast tuyere level (for furnaces of medium and large capacity);
- iron-ore materials shall be located at the height of minimum 11.5–12.0 m from the tuyere level (for furnaces of medium and large capacity);

- blowing-in burden is calculated for production of cast iron of medium grades with the silicon content of 1.5–3.0%;
- blast parameters shall be selected in such a way that the theoretical flame temperature at the tuyeres at the initial period of burden melting is 1850°C and the degree of gas utilization for burden balancing doesn't exceed 0.45.

2. Conclusions

The developed set of the mathematical models, algorithms and software is designed for analysis of furnace blowing-in burden, its arrangement throughout the furnace height, selection of the optimal blast and gas dynamic parameters, which can be used for blowing-in with controlled slag formation and reduction processes. The functional capabilities of the software make it possible to solve quickly the optimization tasks related to selection of the blowing-in burden composition, blast, gas dynamic and slag conditions, to study the influence of different input factors on selection of the blowing-in burden composition and blast parameters.

3. Acknowledgements

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

4. References

[1] Zherebin B N 1980 *Practice of Blast Furnace Operating* (M.: Metallurgy) p 248
[2] Volkov Yu P, Shparber L Ya and Gusarov A K 1986 *Blast Furnace Process Engineer* (M.: Metallurgy) p 26
[3] Ostroukhov M Ya and Shparber L Ya 1976 *Reference Guide of Blast Furnace Foreman* (M.: Metallurgy) p 304
[4] Chernobrivets B F, Kaporulin V V and Zavidonskiy V A 1992 *Practice of Blast-Furnace Production* (M.: Metallurgy) p 111
[5] Kaporulin V V 1989 Steel **6** 17–20
[6] Ulakhovich V A, Mozharenko N M, Netronin V I, Ikkonen A K and Kotov A P 1988 *Steel* **1** 12–18
[7] Spirin N A, Gibadulin M F, Kosachenko I E et al 2006 *Steel* **3** 7–11
[8] Fielden C J and Wood B I 1968 *J. Iron and Steel Inst.* **206** 650–658
[9] Hatano M, Kurita K, Yamaoka H and Yokoi T 1982 *Tetsu-to-Hagane* **68** 2369–76
[10] Taguchi S, Kubo H, Tsuchiya N, Ichifuji K and Okabe K 1982 *Tetsu-to-Hagane* **68** 2303–10
[11] Ramm A N 1980 *Modern Blast-Furnace Process* (M.: Metallurgy) p 304
[12] Spirin N A, Lavrov V V, Rybolovlev V Yu et al 2011 *Model-Based Decision Support Systems in ICS of Blast-Furnace Smelting* (Ekaterinburg: UrFU) p 426