THREE DIMENSIONAL MATHEMATICAL MODEL OF A BLAST FURNACE PROCESS

Ján Terpák, Ľubomír Dorčák, Imrich Koštial
Department of Informatics and Process Control
Faculty of BERG
Technical University of Košice
B. Němcovej 3, 042 00 Košice
Slovak Republic
e-mail : terpak@tuke.sk, phone : (+42195) 6025180

ABSTRACT : In the contribution a three dimensional mathematical model of a blast furnace process is described. In the creation of the model we chose the zonal approach. In each elementary zone we consider the following processes: heat generation (coke burning), heat energy transfer (by convection and conduction), processes of the gas flow through the blast furnace load, the behavior of the most important chemical reactions (oxidation – reduction reactions of iron oxides, carbon oxides dissociation and water evaporation) and smelting of pig iron and slag. The created mathematical model of the blast furnace process can be used as a simulation model of the process, a model of indirect measurement and also as a prediction model in the process control.

Key words : mathematical model, blast furnace, simulation, indirect measurement, control

1. INTRODUCTION

The blast furnace is a countercurrent packed-bed chemical reactor in which gases ascend and reduce descending iron oxide particles. Inputs to the blast furnace are the load (layers of coke and ore) and hot blast. Output from the furnace are blast furnace gas, slag and pig iron [1,2,3].

The developed mathematical model is a tool for simulation of thermal and chemical processes, monitoring and control of the following processes:

- theoretical combustion temperature in front of blast tuyére,
- distribution of gas flow, temperature, and chemical composition,
- temperature profile of blast furnace load,
- position and shape of cohesive zone.

Results of the model will provide information about prereduction load, heat load of the furnace, central and wall gas flow, and non-standard situations.

2. MATHEMATICAL MODEL

The structure of blast furnace model corresponds to the structure of load.. Blast furnace load consists of one layers of coke and ore, sometimes only layers of coke. The load is further divided into sectors and intercircle areas. This division created elementary zones (fig.1) where index i signifes the number of load from the bottom of the furnace, index j is the number of intercircle areas from the furnace axis to furnace wall and index k is the number of sectors in clockwise direction around furnace axis. Every element is defined by the folowing properties:

- number of the element and its six adjacent elements,
- dimension, area and volume of element,
- mass, composition and temperature of load,
- volume, composition and temperature of gas,
- parameters for computation of resistance and value of vertical and horizontal resistance.

For each element following elementary balance is computed:

- balance of gas flow,
- balance of load and gas heat,
- balance of load and gas material.

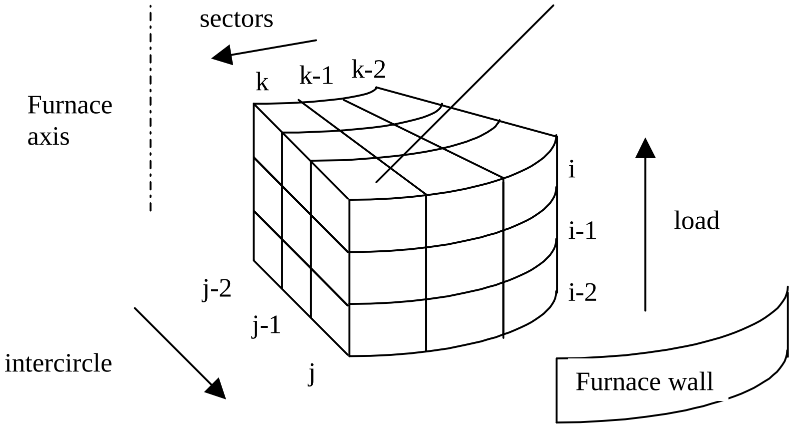

Fig. 1 Division of blast furnace load

3. MODELS OF PARTICULAR PROCESS

From on going processes point of wiev the model is devided into the next particular models:

- generation of heat,
- convection of gas,
- transfer of heat,
- chemical processes,
- process of smelting.

Model of heat generation

Heat generation proceed in the raceway zone in front of blast tuyére. The reducing gases (hydrogen, mono oxide carbon and nitrogen) initially are generated by combusting coke and other injectants (powder coal, oil) with oxygen from the hot blast. The parameter of heat generation is theoretical combustion temperature which is computed from heat balance. This balance includes combustion of carbon to mono oxide carbon, physical heat of hot blast, coke and injectants, and heat for the dissociation of water vapour, injectants and heat for heating reducing gases [4,5].

The theoretical combustion temperature is determined from heat balance equation [1] :

$$T_{teor} = \frac{Q_c + Q_k + Q_v - Q_{dis} + Q_{inj}}{c_{H2}V_{H2} + c_{CO}V_{CO} + c_{N2}V_{N2}}, \quad [\mathrm{K}] \tag{1}$$

where Q_c is the carbon combustion heat from coke and injected fuels [kJ/$kg_{(coke)}$], Q_k is the physical heat of preheating coke [kJ/$kg_{(coke)}$], Q_v is the physical heat of blast air [kJ/$kg_{(coke)}$], Q_{dis} is the dissociation heat of water vapour and injected fuels [kJ/$kg_{(coke)}$], Q_{inj} is the physical heat of injected fuels [kJ/$kg_{(coke)}$], $V_{H2,CO,N2}$ is the volume of H_2, CO and N_2 in the combustion gas [m^3/$kg_{(coke)}$], and $c_{H2,CO,N2}$ is the specific heat capacity of H_2, CO and N_2 [kJ/m^3/K].

Model of gas convection

The model of gas convection determines distribution of gas flow to the element zone. Gas distribution affects subsequent heat transfer conduction and convection, behavior of chemical reactions from termodynamics and kinetics point of view. Parameters of the raceway are defined for initial gas distribution .

For the gas flow under tuyére a heuristic model was used as a function of slag level and parameters of raceway. Above tuyére gas is distributed in horizontal and vertical direction according to the resistance of the load. The specific resistance or permeability of an element zone can be calculated from [6,7]:

$$\frac{1}{R} = 0{,}57\frac{(\varepsilon^3\phi\ D_{str})}{(1-\varepsilon)} \quad , \quad [\mathrm{m}] \tag{2}$$

where ε is the void fraction [$m^3.m^{-3}$], ϕ is the grain shape factor (for the sphere ϕ=1, for others 0,6<ϕ<1) [-], and D_{str} is the particle diameter [m].

Model of heat transfer

The following equation describes stationary heat conduction between adjacent elements or boundary elements and blast furnace wall. [8] :

$$q = -\lambda \frac{dT_v}{dx}, \quad [\mathrm{W.m^{-2}}] \tag{3}$$

and the energy flux for convective heat transfer is defined by Newton-Richman's law [9] :

$$q = \alpha\left(T_v - T_p\right), \quad [\mathrm{W.m^{-2}}] \tag{4}$$

where λ is the thermal conductivity [$W.m^{-1}.K^{-1}$], α is the heat-transfer coefficient [$W.m^{-2}.K^{-1}$], T_v is the temperature of load [K], and T_p is the temperature of gas [K].

We can calculate heat-transfer coefficient by using the equation :

$$Nu = 0{,}37\,\mathrm{Re}^{0,8}\,\mathrm{Pr}^{0,43}\left(\frac{\mathrm{Pr}_p}{\mathrm{Pr}_v}\right)^{0,25}, [-] \tag{5}$$

where Nu is the Nuselt number [-], Re is the Reynolds number [-], and Pr is the Prandtl number [-].

Model of chemical processes

This model uses the following basic chemical reactions of the blast furnace process [10]:

1. Water vaporization :

$$H_2O_{(l)} \rightarrow H_2O_{(g)} \tag{6}$$

2. Carbon oxides dissociation :

$$MeCO_{3(s)} \rightarrow MeO_{(s)} + CO2_{(g)} \tag{7}$$

3. Indirect reduction of iron oxide by carbon monoxide :

$$3Fe_2O_{3(s)} + CO_{(g)} \rightarrow 2Fe_3O_{4(s)} + CO_{2(g)} \tag{8}$$

$$Fe_3O_{4(s)} + CO_{(g)} \rightarrow 3FeO_{(s)} + CO_{2(g)} \tag{9}$$

$$FeO_{(s)} + CO_{(g)} \rightarrow Fe_{(s)} + CO_{2(g)} \tag{10}$$

4. Indirect reduction of iron oxide by hydrogen :

$$3Fe_2O_{3(s)} + H_{2(g)} \rightarrow 2Fe_3O_{4(s)} + H_2O_{(g)} \tag{11}$$

$$Fe_3O_{4(s)} + H_{2\,(g)} \rightarrow 3FeO_{(s)} + H_2O_{\,(g)} \tag{12}$$

$$FeO_{(s)} + H_{2\,(g)} \rightarrow Fe_{(s)} + H_2O_{\,(g)} \tag{13}$$

5. Direct reduction :

$$FeO_{(s)} + C_{(s)} \rightarrow Fe_{(s)} + CO_{(g)} \tag{14}$$

6. Boudouard's reaction :

$$CO_{2(g)} + C_{(s)} \rightarrow 2CO_{(g)} \tag{15}$$

Forward or reverse direction of the chemical reaction is determined by Gibbs free energy in the next equation:

$$\Delta G = \Delta G^o + RT \ln K_a, \quad [\mathrm{J.mol^{-1}}] \tag{16}$$

where ΔG^o is the value of Gibbs free energy in equilibrium state [$J.mol^{-1}$], R is the universal gas constant [$J.mol^{-1}.K^{-1}$], T is the temperature of load [K], and K_a is the equilibrium constant [-].

The change of concentration with time is:

$$c = c_0 e^{-k\Delta\tau}, \quad [\mathrm{mol}] \tag{17}$$

where c_0 is the concentration value of the beginning of the time interval [mol], k is the rate constant [s^{-1}], and Δτ is the time interval [s].

Model of smelting process

The process of smelting is realized in an interval of temperature (for example from 1250 to 1350 °C). This temperature makes the boundary of cohesive zone. For each element zone is computed the temperature of softening and melting as a function of reduction degree of iron oxide. The temperature of zone element is compared with the temperature of softening and melting and then the boundary of cohesive zone is determined (Fig. 2).

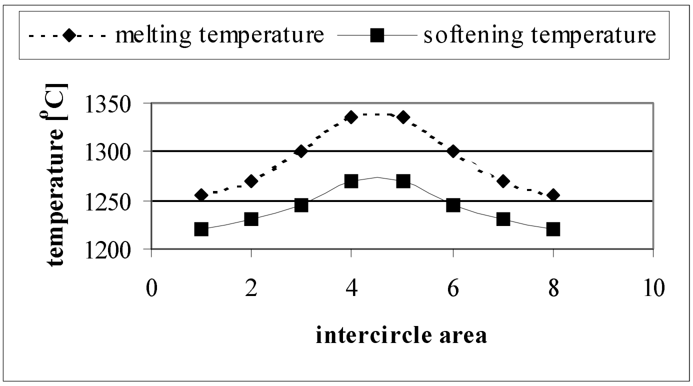

Fig. 2 Temperature of cohesive zone

The mass of smelted is given by the mass and composition of zone element and intensity of smelting. The intensity of smelting is a function of the smelting temperature of the element and smelting temperature of each iron and non iron oxide. The mass, composition, and temperature of a drop of pig iron and slag is determined. The drops then pass through the layers where heat transfer and carbon and silicon dissolution is considered. Then the drops fuse corresponding with pig iron and slag in the blast furnace hearth.

4. CONCLUSION

In the contribution a three dimensional mathematical model is described. This model is determined for dynamical simulation of blast furnace process. Models of particular processes and division of load are given for use in real time. The final aim is to achieve a quantitative simulation of the blast furnace process.

ACKNOWLEDGEMENTS

This work was supported by grant VEGA 1/7098/20 from the Slovak Agency for Science.

REFERENCES

[1] L. Brož: *Teoretické základy výroby surového železa.* SNTL, Praha, 1972

[2] J. G. Peacey and W. G. Davenport: *The Iron Blast Furnace Theory and Practice.* Pergamon Press, Oxford, 1979

[3] I. Omori: *Blast Furnace Phenomena and Modeling.* Elsevier, London, 1987

[4] J. Terpák, Ľ. Dorčák, I. Koštial, M. Olejár: Riadenie teoretickej teploty vo vysokej peci (1). *AT&P Journal,* č.7, ISSN 1335-2237, ročník IV, str.39-41

[5] J. Terpák, Ľ. Dorčák, I. Koštial, M. Olejár: Riadenie teoretickej teploty vo vysokej peci (2). *AT&P Journal,* č.8, ISSN 1335-2237, ročník IV, str.37-38

[6] J. Terpák, Ľ. Dorčák, I. Petráš, I. Koštial, P. Nemčovský: Mathematical Model of Gas Convection in the Blast Furnace Batch. *ASRTP'98 - ICAMC'98, September 8-11, High Tatras, Slovak Republic,* pp. 251-254

[7] J. J. Paveromo: Blast Furnace Burden Distribution Fundamentals. *Iron&Steelmaker,* June, p.46-47

[8] B. Gebhart: *Heat Conduction and Mass Diffusion.* McGraw-Hill, Inc., New York, 1993

[9] W. M. Kays and M. E. Crawford: *Convective Heat and Mass Transfer.* McGraw-Hill, Inc., New York, 1993

[10] J. Terpák, Ľ. Dorčák, I. Koštial, P. Nemčovský: Matematický model vysokopecného procesu. *Proceedings 12th Conference PROCESS CONTROL'99, Volume 2, Tatranské Matliare, High Tatras, Slovak Republic, May 31 – June 3, 1999,* pp. 69-72.