

# THE

**J. G. PEACEY**

Noranda Research Centre, Montreal, Canada

**W. G. DAVENPORT**

McGill University, Montreal, Canada

# IRON

# BLAST

# FURNACE

## Theory and Practice

International Series on Materials Science and Technology, Volume 31



# THE IRON BLAST FURNACE

## *Theory and Practice*

by

J. G. PEACEY

*Noranda Research Centre, Montreal, Canada*

and

W. G. DAVENPORT

*McGill University, Montreal, Canada*



PERGAMON PRESS

OXFORD • NEW YORK • TORONTO • SYDNEY • PARIS • FRANKFURT

# Contents

<b>Preface</b>	<b>xi</b>
<b>Acknowledgements</b>	<b>xiii</b>
 <b>1. A Brief Description of the Blast-Furnace Process</b>	 <b>1</b>
1.1 <i>Raw Materials</i>	1
1.2 <i>Products</i>	7
1.3 <i>Operation</i>	9
1.4 <i>Improvements in Productivity</i>	11
1.5 <i>Blast-furnace costs</i>	12
1.6 <i>Summary</i>	12
<i>Problems</i>	14
 <b>2. A Look Inside the Furnace</b>	 <b>16</b>
2.1 <i>Behaviour in Front of the Tuyères</i>	16
2.2 <i>Reactions in the Hearth, Tuyère Raceways and Bosh</i>	18
2.3 <i>The Fusion Zone</i>	19
2.4 <i>Reduction Above the Fusion Zone</i>	21
2.5 <i>Kinetics of the Coke Gasification Reaction</i>	23
2.6 <i>Reactions in Regions above the 1200 K Isotherm</i>	23
2.7 <i>Reduction of Higher Oxides</i>	23
2.8 <i>The Top Quarter of the Shaft and the Exit Gas</i>	25
2.9 <i>Residence Times</i>	25
2.10 <i>Burden Arrangements</i>	26
2.11 <i>Summary</i>	28
<i>Problems</i>	29
 <b>3. Thermodynamics of the Blast-Furnace Process: Enthalpies and Equilibria</b>	 <b>31</b>
3.1 <i>Enthalpy Requirements in the Blast Furnace</i>	31
3.2 <i>Critical Hearth Temperature</i>	33
3.3 <i>Temperature Profiles in the Furnace: The Thermal Reserve Zone</i>	35
3.4 <i>Free Energy Considerations in the Blast Furnace: The Approach to Equilibrium</i>	36

3.5	<i>Gas Composition Profiles in the Furnace: The Chemical Reserve Zone</i>	38
3.6	<i>Summary</i>	40
	<i>Problems</i>	42
<b>4.</b>	<b>Blast-Furnace Stoichiometry</b>	<b>44</b>
4.1	<i>The Stoichiometric Development</i>	45
4.2	<i>The Stoichiometric Equation</i>	49
4.3	<i>Calculations</i>	50
4.4	<i>Graphical Representation of the Stoichiometric Balance</i>	51
4.5	<i>Summary</i>	56
	<i>Problems</i>	56
<b>5.</b>	<b>Development of a Model Framework: Simplified Blast-Furnace Enthalpy Balance</b>	<b>58</b>
5.1	<i>Simplifications for an Initial Enthalpy Balance</i>	58
5.2	<i>The Enthalpy Balance</i>	59
5.3	<i>Heat Supply and Heat Demand</i>	59
5.4	<i>A General Enthalpy Framework</i>	61
5.5	<i>Summary</i>	63
	<i>Problems</i>	63
<b>6.</b>	<b>The Model Framework: Combination of Stoichiometric and Enthalpy Equations</b>	<b>65</b>
6.1	<i>Combining Stoichiometric and Enthalpy Equations: Calculations</i>	66
6.2	<i>Graphical Representation of the Combined Stoichiometric-Enthalpy Equation</i>	68
6.3	<i>A Graphical Calculation</i>	70
6.4	<i>Summary and Discussion of Stoichiometry/Enthalpy Graph</i>	72
	<i>Problems</i>	74
<b>7.</b>	<b>Completion of the Stoichiometric Part of the Model: Conceptual Division of the Blast Furnace through the Chemical Reserve Zone</b>	<b>75</b>
7.1	<i>The Blast Furnace as Two Separate Reactors</i>	76
7.2	<i>Stoichiometric Balances for the Bottom Segment</i>	78
7.3	<i>Stoichiometric Equation for the Wustite Reduction Zone</i>	80
7.4	<i>Discussion and Summary</i>	81
	<i>Problems</i>	82

<b>8. Enthalpy Balance for the Bottom Segment of the Furnace</b>	<b>84</b>
8.1 <i>Enthalpy Balance for the Bottom Segment</i>	84
8.2 <i>The Demand-Supply Form of the Enthalpy Equation</i>	86
8.3 <i>Numerical Development</i>	88
8.4 <i>Summary</i>	89
<i>Problems</i>	90
<b>9. Combining Bottom Segment Stoichiometry and Enthalpy Equations: <i>a priori</i> Calculation of Operating Parameters</b>	<b>91</b>
9.1 <i>Example Calculations</i>	94
9.2 <i>Implications of the Equations</i>	96
9.3 <i>Graphical Representation of the Equations</i>	98
9.4 <i>A Graphical Calculation</i>	101
9.5 <i>Characteristics of the Operating Line</i>	104
9.6 <i>Summary</i>	106
<i>Problems</i>	106
<b>10. Testing of the Mathematical Model and a Discussion of its Premises</b>	<b>108</b>
10.1 <i>Testing for Thermal Validity</i>	108
10.2 <i>Top-gas Temperature Calculation</i>	110
10.3 <i>Testing for Stoichiometric Validity</i>	113
10.4 <i>Testing for Thermodynamic Validity</i>	114
10.5 <i>Validity of the Model Assumptions and Predictions</i>	114
10.6 <i>Non-attainment of Equilibrium in the Chemical Reserve Zone</i>	117
10.7 <i>Thermal Reserve Temperature Effects</i>	117
10.8 <i>Summary</i>	120
<i>Problems</i>	121
<b>11. The Effects of Tuyère Injectants on Blast-Furnace Operations</b>	<b>123</b>
11.1 <i>A General Injectant</i>	124
11.2 <i>Representing Injected Materials in the Overall Stoichiometric Equation</i>	126
11.3 <i>Representing Injected Materials in the Bottom Segment Stoichiometric Equation</i>	128
11.4 <i>Representing Injected Materials in the Bottom Segment Enthalpy Equation</i>	130
11.5 <i>A Form Convenient for Calculations</i>	133
11.6 <i>Example Calculations: I. Oxygen Enrichment</i>	133
11.7 <i>Example Calculations: II. Hydrocarbon Injection</i>	140
11.8 <i>Graphical Calculations (General Case)</i>	144
11.9 <i>Top-gas Composition with Hydrogen Injection</i>	148
11.10 <i>Discussion of Injection Calculations and Summary</i>	149
<i>Problems</i>	150

<b>12.</b>	<b>Addition of Details into the Operating Equations: Heat Losses; Reduction of Si and Mn; Dissolution of Carbon; Formation of Slag; Decomposition of Carbonates</b>	<b>153</b>
12.1	<i>Stoichiometric Effects</i>	153
12.2	<i>Enthalpy Effects</i>	157
12.3	<i>Summary</i>	164
	<i>Problems</i>	165
<b>13.</b>	<b>Summary of Blast-Furnace-Operating Equations: Comparison between Predictions and Practice</b>	<b>167</b>
13.1	<i>Summary of Model Development Steps</i>	167
13.2	<i>A Strategy for Computer Calculation</i>	173
13.3	<i>Comparison of Model Predictions with Industrial Blast-furnace Data</i>	173
13.4	<i>Effects of Blast Temperature, Tuyère Injectants, Metallized Ore and Metal Impurities on Coke and Blast Requirements</i>	176
13.5	<i>Summary</i>	179
<b>14.</b>	<b>Blast-furnace Optimization by Linear Programming</b>	<b>181</b>
14.1	<i>A Simplified Optimization Problem</i>	182
14.2	<i>Graphical Representation of Cost Minimization</i>	184
14.3	<i>Analytical Optimization Methods</i>	189
14.4	<i>Computer Inputs and Outputs</i>	191
14.5	<i>A More Complete Problem</i>	196
14.6	<i>Summary</i>	202
	<i>Problems</i>	203
<b>Appendix I</b>	<b>Tuyère Flame Temperature Calculations</b>	<b>205</b>
AI.1	<i>Flame Temperature Equations for Linear Programming</i>	208
AI.2	<i>Additional Items in the Calculations</i>	210
<b>Appendix II</b>	<b>Representing Complex Tuyère Injectants in the Operating Equations</b>	<b>212</b>
AII.1	<i>Gaseous Injectants with Known Heats of Combustion and Chemical Compositions</i>	212
AII.2	<i>Injectants with Known Weight Percentages of Carbon and Hydrogen and Known Heats of Combustion</i>	214
<b>Appendix III</b>	<b>Slag Heat Demands</b>	<b>216</b>

<b>Appendix IV</b>	<b>Stoichiometric Data for Minerals and Compounds in Ironmaking</b>	219
<b>Appendix V</b>	<b>Enthalpies of Formation at Temperature <math>T</math> from Elements at Temperature <math>T</math> (<math>H_T^f</math>)</b>	220
<b>Appendix VI</b>	<b>Enthalpy Increment Equations for Elements and Compounds, [<math>H_T^\circ - H_{298}^\circ</math>]</b>	222
<b>Appendix VII</b>	<b>Numerical Values of <math>E^B</math>, Blast Enthalpy</b>	224
	<b>Answers to Numerical Problems</b>	225
	<b>List of Symbols</b>	227
	<b>Index</b>	231



# THE IRON BLAST FURNACE

## Theory and Practice

J. G. PEACEY, Noranda Research Centre, Montreal, Canada

W. G. DAVENPORT, McGill University, Montreal, Canada

An up to date and comprehensive treatment of blast furnaces from fundamental principles through to modern operation procedures. Fundamental equations for the iron blast furnace are developed on the basis of experimental, operational and theoretical data. These equations are used to indicate the relationships between operating variables (raw materials, fuels, fluxes, tuyere injectants, temperatures) and demonstrate how processes should be operated to achieve a specified optimisation goal. Worked examples are provided throughout the text. Each chapter contains a selection of problems and answers are given at the end of the book. Uses SI/Metric units.

**CONTENTS:** A brief description of the blast furnace process. A look inside the furnace. Thermodynamics of the blast furnace process enthalpies and equilibria. Blast furnace stoichiometry. Development of a model framework: simplified blast furnace enthalpy balance. The model framework: combination of stoichiometric and enthalpy equations. Completion of the stoichiometric part of the model: conceptual division of the blast furnace through the chemical reserve zone. Enthalpy balance for the bottom segment of the furnace. Combining bottom segment stoichiometry and enthalpy equations: a priori calculation of operating parameters. Testing of the mathematical model and a discussion of its premises. The effects of tuyere injectants on blast furnace operations. Addition of details into the operating equations: heat losses, reduction of Si and Mn; dissolution of carbon; formation of slag; decomposition of carbonates. Summary of blast furnace operating equations: comparison between predictions and practices. Blast furnace optimisation by linear programming. Appendices.