IRONMAKING AND STEELMAKING
To

Jamsetji Nusserwanji Tata
(3rd March 1839 – 19th May 1904)
Doyen of the Indian Iron and Steel Industry
## Contents

Preface xix

**Part A  GENERAL** 1–23

1. Introduction 1–23
   1.1 Early History of Iron (Steel) 3
      1.1.1 Meteoric Iron and Wrought Iron 3
      1.1.2 Cast Iron 4
      1.1.3 Evolution of Ironmaking in Europe 4
      1.1.4 Early History of Steelmaking before the Advent of Modern Processes 6
      1.1.5 Iron and Steel Heritage of India 7
   1.2 Evolution of Ironmaking Technology Since 1880 8
      1.2.1 The Developing Blast Furnace 8
      1.2.2 Alternative Ironmaking Processes 11
   1.3 Steelmaking Since Henry Bessemer 13
      1.3.1 Bessemer Process 13
      1.3.2 Open Hearth Process 15
      1.3.3 Electric Furnace Steelmaking 15
      1.3.4 Basic Oxygen Steelmaking 16
      1.3.5 Secondary Steelmaking and Continuous Casting of Steel 17
   1.4 Present Status of the World Steel Industry 18
      1.4.1 Classification 18
      1.4.2 World Production of Steel 19
   1.5 Steelmaking in India 19
   1.6 Environmental Pollution and Control 20
      1.6.1 Steps Taken by the Steel Industry 20
      1.6.2 Forms of Pollution 22
   1.7 Concluding Remarks 23

References 23

2. Overview of Blast Furnace Ironmaking 24–38
   2.1 Introduction 24
      2.1.1 Improvements Made in Blast Furnace Technology 25
   2.2 Blast Furnace Reactions and Process in a Nutshell 25
### 2.3 General Constructional Features of the Furnace
- 2.3.1 Different Regions within a Blast Furnace 28
- 2.3.2 Size of Blast Furnace 30

### 2.4 Performance of Blast Furnace 31

### 2.5 Blast Furnace Refractory Lining 32

### 2.6 Charging of Solid Materials from the Top 33

### 2.7 Blast Furnace Plant and Accessories 37
- 2.7.1 Hot Blast Stoves 37

### References 38

### 3. Overview of Modern Steelmaking 39–48

#### 3.1 Introduction 39

#### 3.2 Methods Presently Used for Steel Production 39

#### 3.3 Oxygen Steelmaking 40
- 3.3.1 Top-blown Converter Process 40
- 3.3.2 Bottom-blown Converters (Q-BOP/OBM) 41
- 3.3.3 Bath Agitated Processes 42

#### 3.4 Electric Steelmaking 43
- 3.4.1 Electric Arc Furnace (EAF) 43
- 3.4.2 Electric Induction Furnaces 44

#### 3.5 Secondary Steelmaking 44
- 3.5.1 Ladle Stirring 46
- 3.5.2 Injection Processes 46
- 3.5.3 Vacuum Processes 46
- 3.5.4 Reheating Processes 46

#### 3.6 Continuous Casting 47

### 4. General Physicochemical Fundamentals 49–80

#### 4.1 Introduction 49

#### 4.2 Chemical Equilibrium 49
- 4.2.1 Activity, Free Energy, Chemical Potential and Equilibrium 50
- 4.2.2 Free Energy and Equilibrium 52
- 4.2.3 Oxidation–Reduction Reactions 52

#### 4.3 Activity vs. Composition Relationships 56
- 4.3.1 Introduction 56
- 4.3.2 Ideal, Non-ideal and Regular Solutions 57
- 4.3.3 Activities in Molten Slag Solutions 58
- 4.3.4 Activity–Composition Relationships in Dilute Solutions 58

#### 4.4 Structure and Physicochemical Properties of Melts 64
- 4.4.1 Properties of Liquid Iron and Steel 64
- 4.4.2 Structure and Physicochemical Properties of Slag Melts 66
- 4.4.3 Slag Basicity and Capacities 69
- 4.4.4 Slag Models 71

#### 4.5 Kinetics, Mixing and Mass Transfer 73
- 4.5.1 Introduction 73
- 4.5.2 Interfacial Chemical Reaction 74
- 4.5.3 Diffusion 75
- 4.5.4 Turbulence and Mixing in Fluids 76
- 4.5.5 Convective Mass Transfer at Interface 76
- 4.5.6 Enhancement of Process Rates 78

### References 80
Part B  BLAST FURNACE IRONMAKING

5. Physical Chemistry of Blast Furnace Reactions  83–110

5.1 Thermodynamics of the Carbon–Oxygen Reaction  83
  5.1.1 Combustion of Coke in the Tuyere Zone  83
  5.1.2 C–CO₂–CO Reaction  84

5.2 Gas–Solid Reaction Equilibria in the Blast Furnace Stack  86
  5.2.1 The Fe–O System  86
  5.2.2 Thermodynamics of Reduction of Iron Oxides by Carbon Monoxide  86
  5.2.3 Dissociation of Limestone  89
  5.2.4 Reactions of Hydrogen in the Stack  89

5.3 Kinetics of Reactions in the Stack  91
  5.3.1 Kinetics of Reduction of Iron Oxides by CO and H₂  92
  5.3.2 Kinetics of Gasification of Carbon by CO₂  95
  5.3.3 Kinetics of Reduction of FeO by Carbon  96
  5.3.4 Direct and Indirect Reduction in the Blast Furnace  97

5.4 Reactions and Phenomena in the Blast Furnace Bosh and Hearth  99
  5.4.1 Blast Furnace Slag—Composition and Viscosity  100
  5.4.2 Reaction of Silicon  102
  5.4.3 Reaction of Sulphur  106
  5.4.4 Reactions of Manganese and Titanium  109

References  110

6. Thermal and Chemical Features of the Blast Furnace  111–125

6.1 Introduction  111
  6.1.1 Mass and Heat Balances  111
  6.1.2 Regionwise Heat and Mass Balances  114

6.2 Tuyere Flame Temperature  115
  6.2.1 RAFT Calculations  116
  6.2.2 Tuyere Coal Injection  118

6.3 Thermal and Chemical Reserve Zones  119
  6.3.1 Concept of an Ideal Blast Furnace  119
  6.3.2 Reichardt’s Diagram and Thermal Reserve Zone  120
  6.3.3 Chemical Reserve Zone  121

6.4 The Rist Diagram  122
  6.4.1 Rist Diagram Based on Oxygen Balance Only  122
  6.4.2 Rist Diagram Based on Mass and Heat Balance  123
  6.4.3 Rist Diagram Based on Oxygen and Heat Balance, and Fe–Fe₂O₃–Gas Equilibrium  124

References  125

7. Internal Zones and Gas Flow in Blast Furnaces  126–137

7.1 Introduction  126

7.2 The Six Internal Zones  128

7.3 Aerodynamic Features of the Granular Zone  130
  7.3.1 Ergun Equation for Packed Beds  130
  7.3.2 Bed Fluidisation and Elutriation  132
  7.3.3 Gas Flow Through the Granular Zone of a Blast Furnace  132

7.4 Gas Flow in Wet Zones  135

7.5 Concluding Remarks  136

References  137