

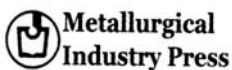
Chi Mei
Jiemin Zhou
Xiaoqi Peng
Naijun Zhou
Ping Zhou

**Simulation and Optimization of Furnaces
and Kilns for Nonferrous Metallurgical
Engineering**

Chi Mei
Jiemin Zhou
Xiaoqi Peng
Naijun Zhou
Ping Zhou

Simulation and Optimization of Furnaces and Kilns for Nonferrous Metallurgical Engineering

With 132 figures



Authors

Prof. Chi Mei
School of Energy Science and Engineering
Central South University, 410083, China
E-mail: meichi3379@gmail.com

Prof. Jiemin Zhou
School of Energy Science and Engineering
Central South University, 410083, China
E-mail: jmzhou@mail.csu.edu.cn

Prof. Xiaoqi Peng
School of Energy Science and Engineering
Central South University, 410083, China
E-mail: pengxq126@126.com

Prof. Naijun Zhou
School of Energy Science and Engineering
Central South University, 410083, China
E-mail: njzhou@mail.csu.edu.cn

Prof. Ping Zhou
School of Energy Science and Engineering
Central South University, 410083, China
E-mail: zhoup@mail.csu.edu.cn

Based on an original Chinese edition:

《有色冶金炉窑仿真与优化》 (Youse Yejin Luyao Fangzhen Yu Youhua), Metallurgical Industry Press, 2001.

ISBN 978-7-5024-4636-9

Metallurgical Industry Press, Beijing

ISBN 978-3-642-00247-2

e-ISBN 978-3-642-00248-9

Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2009920461

© Metallurgical Industry Press, Beijing and Springer-Verlag Berlin Heidelberg 2010

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: Frido Steinen-Broo, Estudio Calamar, Spain

Printed on acid-free paper

Springer is part of Springer Science+Business Media(www.springer.com)

Authors

Prof. Chi Mei

School of Energy Science and Engineering, Central South University, 410083, China

E-mail: meichi3379@gmail.com

Based on an original Chinese edition:

《有色冶金炉窑仿真与优化》(Youse Yejin Luyao Fangzhen Yu Youhua), Metallurgical Industry Press, 2001.

图书在版编目 (CIP) 数据

有色冶金炉窑仿真与优化: 英文 / 梅焱等著.—北京: 冶金工业出版社, 2010
(冶金反应工程学丛书)

ISBN 978-7-5024-4636-9

I. 有… II. 梅… III. ①有色冶金炉—计算机仿真—英文 ②有色冶金炉—最佳化—英文 IV. TF806

中国版本图书馆 CIP 数据核字 (2010) 第 162201 号

ISBN 978-7-5024-4636-9	Metallurgical Industry Press, Beijing
ISBN 978-3-642-00247-2	Springer Heidelberg Dordrecht London New York
e-ISBN 978-3-540-00248-9	Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2009920461

© Metallurgical Industry Press, Beijing and Springer-Verlag Berlin Heidelberg 2010

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: Frido Steinen-Broo, Estudio Calamar, Spain

Printed on acid-free paper

199.00 元

Springer is part of Springer Science+Business Media(www.springer.com)

(仅限中国大陆地区销售)

Preface

Due to the tremendous variety of nonferrous metals and their processes of extraction, the furnaces and kilns used for nonferrous metallurgical engineering (FKNME) vary largely in terms of structure, heating mechanism and functionality. The incomplete statistics show that currently there are over one hundred types of FKNME around the world. Despite this wide variety, however, these FKNME share a few characteristics in common: first of all, most FKNME are heavily energy-consuming, with low energy utilization effectiveness usually ranging from 15% to 50%. The energy needed to extract nonferrous metals is approximated 2.5 to 25 times that for ferrous metals. China is facing an even bigger challenge in this area. The mean energy consumption rates in China are much higher than that of the most advanced indices in the world. Secondly, FKNME usually generate more toxic emissions such as sulfur dioxide, fluoride, chloride, arsenide, etc. Thirdly, the performance of the FKNME is often influenced by many factors, the effects of which are usually non-linear and considerable hysteresis can be found. These difficulties account for the relatively lower process controllability and lower automatization level of the FKNME.

It is clear, from the three common characteristics described above, that the FKNME practices are challenging for the industry and therefore deserve more strenuous investigation. For the purpose of effectively upgrading FKNME technologies and improving performance, it is imperative that the following issues be addressed and resolved. Firstly, the output should be maximized by improving the efficiencies of both thermal and production processes. Secondly, the quality control of the production should be more stringent so as to minimize contaminations in the products and the losses of the useful elements. Thirdly, a longer service life of the FKNME can be achieved by reducing the consumption of the refractory and other construction materials. The fourth and the fifth issues are respectively the reduction of the energy consumption and the pollution emissions. The last two issues are highly correlated; reducing energy consumption normally leads to reduction of emissions (such as SO_x , CO_2 , NO_x , CO and soot). As a matter

of fact, energy consumption can be similarly reduced by augmenting output rate, improving production quality and extending service life. These five issues, therefore, are linked to each other, and may be categorized as the three “highs” (output rate, quality and service life) and two “lows” (energy consumption and pollution emission). Essentially, achieving the objectives of technological upgrading and innovation for the FKNME are equivalent to achieving the overall systematic optimization among the “three highs and two lows”.

Back to the 1950s, G. L. Giomidovskij, a researcher from the former Soviet Union, conducted a series of primitive but quantitative investigations into the fluid flows, fuel combustion, heat transfer and mass transport as well as the physico-chemical reactions in a number of most frequently used FKNME. His work has had a far-reaching impact on the researches on the FKNME. However, due to the unavoidably limited research tools available to him—computation facilities, in particular—the results of his work, at best, provided general information. It was not until the 1970s that the investigations of the FKNME evolved from being limited within macro-phenomena and lumped, averaged information to exploring the micro-mechanism and obtaining fields information. Such change was mainly a result of extensive and rapid development of the computational fluid dynamics (CFD), as well as heat transfer and combustion techniques, thanks to the unprecedented development of the modern information and computer technologies.

As early as the 1980s, the author of this book began applying numerical simulation techniques to investigate the aluminum reduction cells that are among the most widely and frequently used FKNME. The optimized cell lining structures under different operation conditions and system setups were identified by carrying out numerical experiments, i.e., simulations. In the meantime, the research group led by the author used the same methodology to carry out a series of investigations, such as the optimization of the inner wall profiles of the resistance furnaces, and the temperature field prediction and the optimization of the sodberg electrode in the electro-thermal ore-smelting furnaces. The outcomes of these investigations have been proven to be much more effective and accurate than what could be achieved by using the “traditional” research methodology.

As the computation capacity has been continuously improved, the research interests of the group have been extended to the investigations of electric furnaces, flame furnaces, muffle furnaces, bath smelting furnaces and boilers. The research scope has also broadened from single-process simulations and single-objective optimizations to multi-process coupling simulations and multi-objective optimizations. Besides mathematical modeling, artificial intelligence modeling has also been adopted to enable more powerful simulations. Thanks to this progress, the research group has been able to develop various tools for industrial applications. These tools range from the CAD packages for FKNME optimization

and decision-making support systems for operation optimization to the integrated FKNME operational management systems featuring unified platforms for monitoring, controlling and managing.

Throughout decades of investigations, a new research methodology for FKNME has gradually taken shape and been consistently used in recent years in the research group. This methodology, called the “hologram simulation”, requires at first building up a mathematical or artificial intelligence model for the furnace or kiln concerned. Based on this model, a computer code can be developed so that comprehensive and detailed simulation can be performed for the furnace or kiln. Details on the hologram simulation will be covered in Chapter 3. With the help of this hologram simulation tool, multi-objective optimization of the furnace or kiln can be accomplished by systematically carrying out numerical experiments with or without human intervention.

Many people have been involved in work reported in the book. The authors are much indebted to their colleagues and students who participated in the research activities. We would also thank colleagues and friends who contributed to the contents of this book with their ideas and suggestions. Moreover, our deep gratitude is given to Dr. Zhuo Chen for her great efforts in editing the whole book; and special thanks are given to Mr.&Mrs. Ames in Sheffield, U.K., Dr. Siow Yeow at Purdue University, U.S.A. and Prof. Chengping Zhang at Central South University for their careful proofreading of the manuscripts. Without all their work and help, this book would not have been accomplished.

It is our sincere hope that this book would serve as a bridge, helping to exchange academic ideas among the FKNME fellow researchers and developers around the world. We hope the work we have done is useful for colleagues in relative fields. Finally, we wish further development and success in the FKNME research, and we should much welcome any comments on the book that readers may care to send.

Mei Chi
May 2009

Contents

1 Introduction	1
1.1 Classification of the Furnaces and Kilns for Nonferrous Metallurgical Engineering (FKNME).....	1
1.2 The Thermophysical Processes and Thermal Systems of the FKNME.....	2
1.3 A Review of the Methodologies for Designs and Investigations of FKNME.....	4
1.3.1 Methodologies for design and investigation of FKNME	4
1.3.2 The characteristics of the MHSO method.....	5
1.4 Models and Modeling for the FKNME.....	7
1.4.1 Models for the modern FKNME.....	7
1.4.2 The modeling process	7
References.....	9
2 Modeling of the Thermophysical Processes in FKNME	11
2.1 Modeling of the Fluid Flow in the FKNME	11
2.1.1 Introduction.....	11
2.1.2 The Reynolds-averaging and the Favre-averaging methods	13
2.1.3 Turbulence models	15
2.1.4 Low Reynolds number $k-\varepsilon$ models.....	21
2.1.5 Re-Normalization Group (RNG) $k-\varepsilon$ models.....	25
2.1.6 Reynolds stresses model(RSM).....	26
2.2 The Modeling of the Heat Transfer in FKNME	27
2.2.1 Characteristics of heat transfer inside furnaces	27
2.2.2 Zone method	29
2.2.3 Monte Carlo method	33
2.2.4 Discrete transfer radiation model.....	35
2.3 The Simulation of Combustion and Concentration Field.....	38
2.3.1 Basic equations of fluid dynamics including chemical reactions....	38
2.3.2 Gaseous combustion models.....	42

2. 3. 3	Droplet and particle combustion models	48
2. 3. 4	NO _x models	54
2. 4	Simulation of Magnetic Field	60
2. 4. 1	Physical models	60
2. 4. 2	Mathematical model of current field	61
2. 4. 3	Mathematical models of magnetic field in conductive elements.....	62
2. 4. 4	Magnetic field models of ferromagnetic elements	66
2. 4. 5	Three-dimensional mathematical model of magnetic field	69
2. 5	Simulation on Melt Flow and Velocity Distribution in Smelting Furnaces.....	69
2. 5. 1	Mathematical model for the melt flow in smelting furnace	70
2. 5. 2	Electromagnetic flow	71
2. 5. 3	The melt motion resulting from jet-flow	75
	References	80
3	Hologram Simulation of the FKNME	87
3. 1	Concept and Characteristics of Hologram Simulation	87
3. 2	Mathematical Models of Hologram Simulation	89
3. 3	Applying Hologram Simulation to Multi-field Coupling.....	92
3. 3. 1	Classification of multi-field coupling	92
3. 3. 2	An example of intra-phase three-field coupling	93
3. 3. 3	An example of four-field coupling	94
3. 4	Solutions of Hologram Simulation Models	97
	References	98
4	Thermal Engineering Processes Simulation Based on Artificial Intelligence.....	101
4. 1	Characteristics of Thermal Engineering Processes in Nonferrous Metallurgical Furnaces	101
4. 2	Introduction to Artificial Intelligence Methods	102
4. 2. 1	Expert system.....	103
4. 2. 2	Fuzzy simulation.....	104
4. 2. 3	Artificial neural network.....	106
4. 3	Modeling Based on Intelligent Fuzzy Analysis	107
4. 3. 1	Intelligent fuzzy self-adaptive modeling of multi-variable system	108
4. 3. 2	Example: fuzzy adaptive decision-making model for nickel matte smelting process in submerged arc furnace	111
4. 4	Modeling Based on Fuzzy Neural Network Analysis.....	116
4. 4. 1	Fuzzy neural network adaptive modeling methods of multi-variable system	117

4. 4. 2	Example: fuzzy neural network adaptive decision-making model for production process in slag cleaning furnace.....	120
References	123
5	Hologram Simulation of Aluminum Reduction Cells.....	127
5. 1	Introduction.....	127
5. 2	Computation and Analysis of the Electric Field and Magnetic Field....	131
5. 2. 1	Computation model of electric current in the bus bar	132
5. 2. 2	Computational model of electric current in the anode.....	133
5. 2. 3	Computation and analysis of electric field in the melt	134
5. 2. 4	Computation and analysis of electric field in the cathode.....	138
5. 2. 5	Computation and analysis of the magnetic field.....	140
5. 3	Computation and Analysis of the Melt Flow Field.....	146
5. 3. 1	Electromagnetic force in the melt.....	147
5. 3. 2	Analysis of the molten aluminum movement	148
5. 3. 3	Analysis of the electrolyte movement	149
5. 3. 4	Computation of the melt velocity field.....	150
5. 4	Analysis of Thermal Field in Aluminum Reduction Cells	152
5. 4. 1	Control equations and boundary conditions	153
5. 4. 2	Calculation methods.....	156
5. 5	Dynamic Simulation for Aluminum Reduction Cells.....	158
5. 5. 1	Factors influencing operation conditions and principle of the dynamic simulation	159
5. 5. 2	Models and algorithm	160
5. 5. 3	Technical scheme of the dynamic simulation and function of the software system	161
5. 6	Model of Current Efficiency of Aluminum Reduction Cells.....	163
5. 6. 1	Factors influencing current efficiency and its measurements.....	164
5. 6. 2	Models of the current efficiency	166
References	169
6	Simulation and Optimization of Electric Smelting Furnace	175
6. 1	Introduction.....	175
6. 2	Sintering Process Model of Self-baking Electrode in Electric Smelting Furnace.....	176
6. 2. 1	Electric and thermal analytical model of the electrode.....	178
6. 2. 2	Simulation software	182
6. 2. 3	Analysis of the computational result and the baking process.....	183
6. 2. 4	Optimization of self-baking electrode configuration and operation regime	190
6. 3	Modeling of Bath Flow in Electric Smelting Furnace.....	192

6. 3. 1	Mathematical model for velocity field of bath	193
6. 3. 2	The forces acting on molten slag	194
6. 3. 3	Solution algorithms and characters.....	196
6. 4	Heat Transfer in the Molten Pool and Temperature Field	
	Model of the Electric Smelting Furnace.....	198
6. 4. 1	Mathematical model of the temperature field in the molten pool.....	199
6. 4. 2	Simulation software	203
6. 4. 3	Calculation results and verification	203
6. 4. 4	Evaluation and optimization of the furnace design and operation	208
	References.....	210
7	Coupling Simulation of Four-field in Flame Furnace.....	213
7. 1	Introduction.....	213
7. 2	Simulation and Optimization of Combustion Chamber of Tower-Type Zinc Distillation Furnace.....	215
7. 2. 1	Physical model.....	216
7. 2. 2	Mathematical model.....	217
7. 2. 3	Boundary conditions	217
7. 2. 4	Simulation of the combustion chamber prior to structure optimization	218
7. 2. 5	Structure simulation and optimization of combustion chamber.....	220
7. 3	Four-field Coupling Simulation and Intensification of Smelting in Reaction Shaft of Flash Furnace	221
7. 3. 1	Mechanism of flash smelting process—particle fluctuating collision model	223
7. 3. 2	Physical model.....	224
7. 3. 3	Mathematical model—coupling computation of particle and gas phases	225
7. 3. 4	Simulation results and discussion.....	227
7. 3. 5	Enhancement of smelting intensity in flash furnace.....	229
	References.....	232
8	Modeling of Dilute and Dense Phase in Generalized Fluidization	235
8. 1	Introduction.....	235
8. 2	Particle Size Distribution Models	238
8. 2. 1	Normal distribution model.....	239
8. 2. 2	Logarithmic probability distribution model.....	240
8. 2. 3	Weibull probability distribution function	241

8. 2. 4	R-R distribution function (Rosin-Rammler distribution).....	241
8. 2. 5	Nukiyawa-Tanasawa distribution function.....	242
8. 3	Dilute Phase Models.....	244
8. 3. 1	Non-slip model.....	245
8. 3. 2	Small slip model.....	247
8. 3. 3	Multi-fluid model (or two-fluid model).....	248
8. 3. 4	Particle group trajectory model.....	251
8. 3. 5	Solution of the particle group trajectory model.....	256
8. 4	Mathematical Models for Dense Phase.....	257
8. 4. 1	Two-phase simple bubble model.....	258
8. 4. 2	Bubbling bed model.....	259
8. 4. 3	Bubble assemblage model (BAM).....	261
8. 4. 4	Bubble assemblage model for gas-solid reactions.....	265
8. 4. 5	Solid reaction rate model in dense phase.....	267
	References.....	272
9	Multiple Modeling of the Single-ended Radiant Tubes.....	275
9. 1	Introduction.....	275
9. 1. 1	The SER tubes and the investigation of SER tubes.....	276
9. 1. 2	The overall modeling strategy.....	278
9. 2	3D Cold State Simulation of the SER Tube.....	279
9. 3	2D Modeling of the SER Tube.....	283
9. 3. 1	Selecting the turbulence model.....	283
9. 3. 2	Selecting the combustion model.....	286
9. 3. 3	Results and analysis of the 2D simulation.....	289
9. 4	One-dimensional Modeling of the SER Tube.....	291
	References.....	295
10	Multi-objective Systematic Optimization of FKNME.....	297
10. 1	Introduction.....	297
10. 1. 1	A historic review.....	297
10. 1. 2	The three principles for the FKNME systematic optimization.....	298
10. 2	Objectives of the FKNME Systematic Optimization.....	299
10. 2. 1	Unit output functions.....	300
10. 2. 2	Quality control functions.....	305
10. 2. 3	Control function of service lifetime.....	306
10. 2. 4	Functions of energy consumption.....	308
10. 2. 5	Control functions of air pollution emissions.....	309
10. 3	The General Methods of the Multi-purpose Synthetic Optimization.....	309

10. 3. 1	Optimization methods of artificial intelligence	309
10. 3. 2	Consistent target approach	312
10. 3. 3	The main target approach.....	314
10. 3. 4	The coordination curve approach	315
10. 3. 5	The partition layer solving approach	315
10. 3. 6	Fuzzy optimization of the multi targets	316
10. 4	Technical Carriers of Furnace Integral Optimization	318
10. 4. 1	Optimum design CAD	319
10. 4. 2	Intelligent decision support system for furnace operation optimization	320
10. 4. 3	Online optimization system	327
10. 4. 4	Integrated system for monitoring, control and management	330
References	334
Index	337

Contributors

Chi Mei, Professor

Central South University, China

E-mail: meichi@mail.csu.edu.cn

Jiemin Zhou, PhD and Professor

Central South University, China

E-mail: jmzhou@mail.csu.edu.cn

Xiaoqi Peng, PhD and Professor

Central South University, China

E-mail: pegxq126@126.com

Naijun Zhou, PhD and Professor

Central South University, China

E-mail: njzhou@mail.csu.edu.cn

Ping Zhou, PhD and Professor

Central South University, China

E-mail: zhoup@mail.csu.edu.cn

Zhuo Chen, PhD and Associate professor

Central South University, China

E-mail: chenzhuo@mail.csu.edu.cn

Feng Mei, PhD

Central South University, China

E-mail: feng.mei@lastmilecn.com

Shaoduan Ou, PhD

Central South University, China

E-mail: shaoduan@gmail.com

Hongrong Chen, MD

Central South University, China

E-mail: hrchen@mail.csu.edu.cn

Yanpo Song, MD

Central South University, China

E-mail: songyanpo@mail.csu.edu.cn

Junfeng Yao, PhD and Associate professor

Xiamen University, China

E-mail: yao0010@yahoo.com.cn

Kai Xie, PhD and Associate professor

Central South University, China

E-mail: xiekaicsu@163.com

Hui Cai, MD

Changsha Engineering and Research Institute of Nonferrous Metallurgy,
China

E-mail: caihuicaihui@163.com

List of Contributors

Chapter 1

Chi Mei

Professor
Central South University
Email: eichi@mail.csu.edu.cn

Hongrong Chen

Central South University
Email: hrchen@mail.csu.edu.cn

Chapter 2

Ping Zhou

PhD and Professor
Central South University
Email: zhoup@mail.csu.edu.cn

Feng Mei

PhD
Central South University
Email: feng.mei@lastmilecn.com

Hui Cai

Changsha Engineering and Research
Institute of Nonferrous Metallurgy
Email: caihuicaihui@163.com

Chapter 3

Chi Mei

Zhuo Chen

PhD and Associate professor
Central South University
Email: chenzhuo@mail.csu.edu.cn

Chapter 4

Xiaoqi Peng

PhD and Professor
Central South University
Email: pengxq126@126.com

Yanpo Song

Central South University
Email: songyanpo@mail.csu.edu.cn

Chapter 5

Naijun Zhou

PhD and Professor
Central South University

Email: njzhou@mail.csu.edu.cn

Chapter 6

Jiemin Zhou

PhD and Professor

Central South University

Email: jmzhou@mail.csu.edu.cn

Ping Zhou

Chapter 7

Ping Zhou

Zhuo Chen

Kai Xie

PhD and Associate professor

Central South University

Email: xiekaicsu@163.com

Chapter 8

Chi Mei

Shaoduan Ou

Central South Univeristy

Email: shaoduan@gmail.com

Chapter 9

Feng Mei

Chapter 10

Xiaoqi Peng

Yanpo Song

Zhuo Chen

Junfeng Yao

Xiamen University

Email: yao0010@yahoo.com.cn