

Engineering in Process Metallurgy

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Oxford New York Toronto
Delhi Bombay Calcutta Madras Karachi
Petaling Jaya Singapore Hong Kong Tokyo
Nairobi Dar es Salaam Cape Town
Melbourne Auckland

and associated companies in Berlin Ihadan

Oxford is a trade mark of Oxford University Press

Published in the United States by Oxford University Press, New York

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British Library Cataloguing in Publication Data
Guthrie, R. I. L.
Engineering in process metallurgy.
1. Chemical metallurgy
I. Title
669'.9
ISBN 0-19-856222-5

Library of Congress Cataloging in Publication Data
Guthrie, R. I. L.
Engineering in process metallurgy.
Includes bibliographies and index.

1. Metallurgy. 2. Heat—Transmission. 3. Mass transfer. 1. Title.
TN665.G95 1988 669 87-35026
ISBN 0-19-856222-5

Typeset by Macmillan India Ltd, Printed and bound in Great Britain by Biddles Ltd, Guildford and King's Lynn

PREFACE

The last twenty years have witnessed much progress aimed at improving and controlling the kinetics of metallurgical processing operations.

Thanks to continued advances, metal products of higher chemical and physical quality are now being produced more efficiently than ever before. In a highly competitive world, all metallurgical graduates working in the processing industries need to understand the central role that heat, mass, and momentum transport phenomena play in determining process kinetics. Similarly, they need to learn how thermodynamic relationships, or equilibria, must form an integral part of process kinetics, and how these can be incorporated into the subject.

The primary purpose of this text, therefore, is to provide a fairly comprehensive, but basic, treatment of process engineering metallurgy. While many books have been written on the subject of transport phenomena for chemical and mechanical engineers, and these are of value to the process metallurgist, most of the examples and illustrations cited are naturally external to the field (of process metallurgy). Further, many of the texts are too extensive, or specialized, for easy incorporation into a metallurgical/materials science curriculum.

On the other side, many practising mechanical/chemical engineers entering the metallurgical field will not normally have been exposed to the peculiar features of metallurgical operations; these include very high processing temperatures, and unusual fluids (e.g. liquid metals and slags), whose chemical and physical properties can result in phenomena unique to metallurgical, as opposed to chemical, engineering. Similarly, their background in chemical, rather than metallurgical, thermodynamics will tend to make their knowledge of mass transport phenomena more difficult to apply.

Since the amount of time devoted to process metallurgy varies markedly from one curriculum to another, the present text has been written to take this into account, and can be ingested piecewise, as it is divided into four major components.

Chapter 1 introduces the subject, illustrating the role of transport phenomena in typical metallurgical operations. It goes on to present the fundamental or atomistic, origin of those transport coefficients governing the flow of momentum, heat, and mass within a system. Radiation properties are also presented at this point.

Chapters 2 and 3 go on to treat fluid statics, and then fluid dynamics in metallurgy, followed by process modelling techniques, using a series of colevant examples.

Chapter 4 provides an integrated approach to the subject of conductive heat flow, and diffusion in solids (or other stationary systems), leading into

Chapter 5, where the effects of convection on heat and mass flows are incorporated.

Chapter 6 completes the text, introducing the reader to the numerical modelling of metallurgical processes, and demonstrating the various techniques whereby complex metallurgical operations can be both successfully analysed and synthesized.

In presenting the subject matter in this way, the book reflects three courses (heat and mass transfer, fluid dynamics, numerical modelling) presented to a generation of patient McGill students. Many worked examples are presented to illustrate the subject areas. A series of relevant exercises, often dealing with actual industrial examples the author has encountered over the past twenty years, are also included for study.

In conclusion, it is hoped that this book can provide a starting point for the metallurgical student or graduate entering the processing industry. Equally, the text can provide valuable orientation to engineers or scientists of a different background, but working, or about to enter, the metallurgical processing industries. Given the extensive data on physical properties, together with appendices providing useful thermodynamic data, and conversion factors, it is hoped that the text can also be used as a quick reference source and workbook.

McGill University February 1987 R. I. L. G.

ACKNOWLEDGEMENTS

The author would like to acknowledge the influence of his various instructors at Imperial College some twenty years ago when Process Engineering Metallurgy was in its infancy: Professor F. D. Richardson, for his leadership in introducing the subject to the undergraduate curriculum, and showing its intrinsic coupling with metallurgical thermodynamics, Professor A. V. Bradshaw for his pragmatic and realistic approach to the subject, Professor J. Szekely for his theoretical insights, and Professor A. W. D. Hills for his superb teaching skills. The subject has now come of age and its demonstrated accomplishments such as fully three-dimensional, transient models of blast furnace behaviour, rank with the very best in equivalent disciplines.

In preparing this book, the author deeply appreciates the knowledge he has gained conducting research with his various graduate students, research associates, and visiting professors while at McGill (R. Anantharayanan, S. Argyropoulos, I. Cameron, F. M. Chiesa, F. Dallaire, D. Doutre, D. Frayce, L. Gourtsoyannis, J.-W. Han, M. Hasat, J. Herbertson, D. Holford, T. Iida, C. Jefferies, S. Joo, A. Kadoglou, J. Kamal, S.-H. Kim, B. Kulunk, S. Kuyucak, H.-C. Lee, D. Mazumdar, F. Mucciardi, H. Nakajima, E. Ozberk, R. Perrin, Y. Sahai, M. Salcudean, M. Y. Solar, A. Storey, M. Tanaka, S. Tanaka, Tian, R. Urquhart, D. Verhelst, and C. Xu).

Particular thanks go to Professor C. Bale of Ecole Polytechnique for help, with the thermodynamic examples, to Dr M. Hasan for help with proof reading and his boundary layer program, and Dr J. Herbertson and Miss P. Khan, for helping assemble the appendices and correlations.

Finally, the author acknowledges the forbearance of his family, in the hope that it was a worthwhile enterprise, even though it took far too long to accomplish.

The author gratefully acknowledges permission to redraw, or reset, the following list of figures and tables from previous publications.

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Figs. 1.16, 1.17	Schack (1965)	York, U.S.A. Academic Press, New
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		Warrendale, PA., U.S.A.
Figs. 1.32–1.34	Iida & Guthrie (1988)	Oxford Univ. Press,
•		Oxford, U.K.
Figs. 1.35, 1.36	Iida & Morita (1975)	Iron & Steel Soc. of AIME,
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	Lightfoot (1966)	New York, U.S.A.
Fig. 2.9	Bird, Stewart &	John Wiley and Sons,
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	(1957)	New York, U.S.A.
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Fig. 2.18	Davies (1972)	Academic Press, New
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5

AN INTRODUCTION TO TRANSPORT PHENOMENA AND PROPERTIES IN METALLURGICAL OPERATIONS

1.0. INTRODUCTION

In today's world of high-level competition, of technical competence, and of relatively low bulk-transportation costs, any company involved in chemical or metallurgical manufacturing must make maximum use of efficient processing operations. For engineers and researchers engaged in the 'avelopment and operation of such practices, a knowledge of thermodynamics and process kinetics is essential.

The present text has been written with this in mind and is intended for those interested in the metallurgical industry. The various concepts of fluid, heat, and mass transfer are therefore introduced by way of a series of metallurgical examples and practical problems.

Since useful solutions to many industrial design problems are readily obtained without one having to become too deeply involved in the detailed complexities of transport phenomena, care has been taken to avoid unnecessary complications in the treatment. The reader is therefore referred to the specialist literature for more detailed and exhaustive treatments of the various topics and processes discussed in the present text.

1.1. EXAMPLES OF HEAT AND MASS TRANSFER IN METALLURGICAL ENGINEERING

Practically all metallurgical processing operations involve, in one way or another, fluid flow and the transfer of heat and/or mass. To illustrate this statement and to familiarize the reader with some typical metallurgical operations, it is worthwhile to look briefly at some of the heat, mass, and momentum transfer aspects involved in steel-making. Figure 1.1 illustrates the sequence of operations typically performed in going from raw iron oxides to steel.

(a) Coke-making

The first major operation (Fig. 1.2) involves the production of coke, which is required for the reduction of iron oxides to iron. The process involves the destructive distillation of metallurgical grade coals in coking chambers (sealed

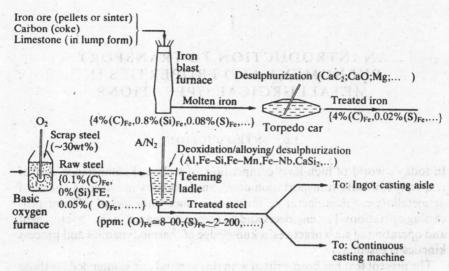


Fig. 1.1. Schematic flowsheet showing the major operations conventionally used for converting iron into raw steel.

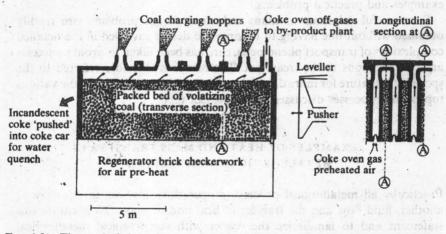


Fig. 1.2. The vertical slot coke oven for the production of metallurgical grade coke for the iron blast furnace.

vertical slots 4 m high, 12 m wide, 0.5 m thick) of by-product coke ovens. The heat needed for distillation of the volatiles is transferred through the brickwork from adjacent vertical flues by combustion of enriched blast furnace off-gases. After about 17 hours' induction time, the incandescent coke is pushed out into transfer railway cars. During its fall, it breaks apart to form large lumps. The coke lumps are then transferred to the quenching tower, in

which an intense and normally intermittent water spray quenches them for subsequent charging to the blast furnace.

This quenching procedure is an interesting example of heat transfer, in that the heat transferred from the inner portions of the coke lumps vaporizes the water running down their external surfaces. The overall operation involves the emission of vast plumes of steam (as well as certain undesirable vapours such as phenols and cyanides). The objectives here are to ensure the minimum amount of retained moisture in the coke, its endothermic effects contributing to poor fuel efficiency in the blast furnace.

(b) Blast furnance

The iron-making blast furnace (Fig. 1.3), has evolved over many hundreds of years to become an efficient countercurrent exchanger of heat and countercurrent exchanger of mass (i.e., of oxygen). Thus iron oxide (as pellets or sinter), together with coke and limestone, are successively charged through the top of the furnace. The charge slowly descends through the shaft (an eighthour journey) and is gradually heated by hot ascending gases. As the gas lower down the furnace is richer in carbon monoxide, and therefore more reducing towards iron oxides, the pellets are gradually reduced as a result of mass transfer of carbon monoxide (and hydrogen) from the gas phase into the pellet, i.e.

$$3Fe_2O_3+CO\rightarrow 2Fe_3O_4+CO_2$$

 $Fe_3O_4+CO\rightarrow 3FeO+CO_2$

Final deoxidation is accomplished down in the cohesive zone where high temperatures and highly reducing conditions result in the reduction of wustite (FeO) to iron. Impurities such as silica, sulphur, alumina, and magnesia, present in the original pellets associate with the lime and are removed as a molten slag.

The final reduction from FeO takes place via mass transfer mechanisms:

1 and
$$\begin{cases} FeO + CO \rightarrow Fe + CO_2 \\ CO_2 + C(coke) \rightarrow 2CO \end{cases}$$
 Indirect reduction
$$2 \qquad FeO + C \rightarrow Fe + CO \qquad Direct reduction$$

The CO/CO₂ reaction is often termed the solution loss reaction (i.e., dissolution of coke by CO₂). Although the purpose of the coke is obviously to act as a reductant, it also plays another critical role in that it behaves as a supporting pillar for overlaying burden. In the region below the cohesive (or 'sticky') zone in Fig. 1.3, everything else is molten or melting (i.e., slag and pig iron).