The background of the cover is a deep teal color with a subtle, repeating pattern of white roses. The roses are arranged in a grid-like fashion, with each rose slightly offset from the others, creating a sense of depth and texture. The overall aesthetic is clean and professional.

**Handbook of**  
**Drying**  
**for Dairy**  
**Products**

Edited by  
**C. Anandharamakrishnan**

**WILEY** Blackwell



## **Handbook of Drying for Dairy Products**



# Handbook of Drying for Dairy Products

*Edited by C. Anandharamakrishnan*

*Indian Institute of Crop Processing Technology  
Thanjavur, Tamil Nadu  
India*

**WILEY** Blackwell

This edition first published 2017 © 2017 John Wiley & Sons Ltd

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at <http://www.wiley.com/go/permissions>.

The right of C. Anandharamakrishnan to be identified as the author of the editorial material in this work has been asserted in accordance with law.

*Registered Offices*

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

*Editorial Office*

9600 Garsington Road, Oxford, OX4 2DQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at [www.wiley.com](http://www.wiley.com).

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

*Limit of Liability/Disclaimer of Warranty*

The publisher and the authors make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of fitness for a particular purpose. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for every situation. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of experimental reagents, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each chemical, piece of equipment, reagent, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. The fact that an organization or website is referred to in this work as a citation and/or potential source of further information does not mean that the author or the publisher endorses the information the organization or website may provide or recommendations it may make. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. No warranty may be created or extended by any promotional statements for this work. Neither the publisher nor the author shall be liable for any damages arising herefrom.

*Library of Congress Cataloging-in-Publication Data:*

Names: Anandharamakrishnan, C., editor.

Title: Handbook of drying for dairy products / edited by

Dr. C. Anandharamakrishnan.

Description: Chichester, UK ; Hoboken, NJ : John Wiley & Sons, 2017. |

Includes bibliographical references and index.

Identifiers: LCCN 2016047616 | ISBN 9781118930496 (cloth) | ISBN 9781118930502 (epub)

Subjects: LCSH: Dairy products—Drying.

Classification: LCC SF250.5 .H36 2017 | DDC 637—dc23 LC record available at <https://lccn.loc.gov/2016047616>

Cover image: Atropat/Gettyimages

Cover design: Wiley

Set in 10/12pt Warnock by SPi Global, Chennai, India

## Contents

<b>Contributors</b>	<i>xiii</i>
<b>About the editor</b>	<i>xv</i>
<b>Preface</b>	<i>xvii</i>
<b>Acknowledgments</b>	<i>xix</i>

<b>1</b>	<b>Introduction to Drying</b>	<i>1</i>
	<i>C. Anandharamakrishnan</i>	
1.1	Introduction	<i>1</i>
1.2	Fundamental principles of drying: the concept of simultaneous heat and mass transfer	<i>2</i>
1.2.1	Heat transfer during the drying process	<i>2</i>
1.2.1.1	Conduction drying	<i>3</i>
1.2.1.2	Convection drying	<i>4</i>
1.2.1.3	Radiation and dielectric drying	<i>5</i>
1.2.2	Mass transfer during the drying process	<i>6</i>
1.2.2.1	Diffusion mechanism	<i>7</i>
1.2.2.2	Capillary mechanism	<i>8</i>
1.3	The drying curve	<i>9</i>
1.4	Stages of drying	<i>9</i>
1.4.1	Constant rate period	<i>10</i>
1.4.2	Falling rate period	<i>11</i>
1.5	Techniques for the drying of dairy products	<i>12</i>
1.6	Conclusion	<i>13</i>
	References	<i>13</i>
<b>2</b>	<b>Dried Dairy Products and their Trends in the Global Market</b>	<i>15</i>
	<i>Aadinath, T. Ghosh, P.H. Amaladhas and C. Anandharamakrishnan</i>	
2.1	Introduction	<i>15</i>
2.2	Milk powders and dried milk products	<i>16</i>
2.2.1	Primary dairy powders	<i>16</i>
2.2.2	Secondary dairy powders	<i>16</i>
2.3	World market dynamics	<i>18</i>
2.3.1	Production	<i>18</i>
2.3.1.1	Oceania	<i>18</i>
2.3.1.2	India	<i>20</i>

- 2.3.1.3 European Union 20
- 2.3.1.4 Argentina 20
- 2.3.2 Consumption 20
- 2.3.2.1 Algeria 20
- 2.3.2.2 Indonesia 21
- 2.3.2.3 China 21
- 2.3.2.4 Mexico 21
- References 21

### **3 Techniques for the Preconcentration of Milk 23**

*I. Roy, A. Bhushani and C. Anandharamakrishnan*

- 3.1 Introduction 23
- 3.2 Need for preconcentration 23
- 3.2.1 Skim milk 24
- 3.2.2 Whey powders and infant formula 24
- 3.3 Concentration methods 25
- 3.4 Thermal methods 25
- 3.4.1 Evaporation 25
- 3.4.1.1 Single-effect recirculation evaporator 25
- 3.4.1.2 Multiple-effect evaporator 26
- 3.4.1.3 Falling-film evaporator 27
- 3.4.1.4 Plate evaporator 28
- 3.4.1.5 Horizontal tube evaporator 30
- 3.4.1.6 Mechanical film evaporator 30
- 3.4.1.7 Low-temperature evaporator 30
- 3.5 Non-thermal methods 30
- 3.5.1 Freeze concentration 30
- 3.5.2 Membrane separation techniques 32
- 3.5.2.1 Microfiltration 34
- 3.5.2.2 Ultrafiltration 35
- 3.5.2.3 Reverse osmosis 37
- 3.6 Conclusion 37
- References 37

### **4 Drum Drying 43**

*P. Karthik, N. Chhanwal and C. Anandharamakrishnan*

- 4.1 Introduction 43
- 4.2 Drum-drying process 44
- 4.2.1 Effect of operating parameters on product quality and the capacity of the drum dryer 45
- 4.3 Types of drum dryers 46
- 4.3.1 Single-drum dryers 46
- 4.3.2 Double-drum dryers 47
- 4.3.3 Twin-drum dryers 47
- 4.3.4 Vacuum-drum dryers 48
- 4.3.5 Enclosed-drum dryers 49
- 4.4 Classification of the feeding method 49
- 4.4.1 Single- and multiple-roll feed 49

4.4.2	Nip feed	49
4.4.3	Dip feed	49
4.4.4	Spray feed	49
4.4.5	Splash feed	50
4.5	Operating parameters	51
4.5.1	Important operational conditions in the drum drying of milk	52
4.6	Advantages and disadvantages of drum/roller drying	54
4.7	Conclusion	54
	References	55
<b>5</b>	<b>Spray Drying</b>	<b>57</b>
	<i>S. Padma Ishwarya and C. Anandharamakrishnan</i>	
5.1	Introduction	57
5.2	Spray drying: principle of operation	57
5.2.1	Atomization	59
5.2.1.1	Rotary atomizers	60
5.2.1.2	Pressure nozzle atomizers	62
5.2.1.3	Twin-fluid atomizers	62
5.2.1.4	Monodisperse droplet generators	63
5.2.2	Droplet–drying air interaction and moisture evaporation	65
5.2.3	Particle separation	72
5.3	Characteristics of spray-dried dairy powders	74
5.3.1	Rehydration	74
5.3.2	Particle size and shape parameters	75
5.4	Handling spray-drying processing problems	77
5.4.1	Stickiness	77
5.4.2	Thermal denaturation of proteins	79
5.5	Applications of spray drying for the production of dried milk and milk products	79
5.6	Conclusion	84
	References	88
<b>6</b>	<b>Freeze Drying</b>	<b>95</b>
	<i>A. Bhushani and C. Anandharamakrishnan</i>	
6.1	Introduction	95
6.2	Steps in freeze drying	95
6.2.1	Freezing	96
6.2.2	Primary or sublimation drying	99
6.2.3	Secondary or desorption drying	100
6.3	Merits of freeze drying over other drying techniques	100
6.4	Heat and mass transfer in freeze drying	101
6.5	Freeze-drying equipment	103
6.6	Properties influencing the freeze drying of dairy products	106
6.6.1	Milk	106
6.6.2	Lactose	109
6.7	Preservation of kefir culture by freeze drying	111
6.8	Microencapsulation of probiotics by freeze drying	112
6.8.1	Probiotics	112

- 6.8.2 Need for microencapsulation 113
- 6.8.3 Cell viability issues associated with freeze drying 113
- 6.8.4 Characteristics of microencapsulated probiotic cells 114
- 6.9 Conclusion 115
- References 117
  
- 7 Spray Freeze Drying 123**  
*S. Padma Ishwarya, C. Anandharamakrishnan and A.G.F. Stapley*
- 7.1 Introduction 123
- 7.2 SFD process 124
- 7.2.1 Atomization 125
- 7.2.2 Freezing 126
- 7.2.2.1 Spray freezing into vapour 127
- 7.2.2.2 Spray freezing into vapour over liquid 127
- 7.2.2.3 Spray freezing into liquid 129
- 7.2.3 Freeze drying 130
- 7.2.3.1 Vacuum freeze drying 130
- 7.2.3.2 Atmospheric SFD and atmospheric spray fluidized-bed freeze drying 131
- 7.2.3.3 Sub-atmospheric pressure SFD 132
- 7.3 Applications of SFD in dried dairy products 132
- 7.3.1 SFD of whole milk and skim milk 133
- 7.3.2 SFD of whey protein 135
- 7.3.3 SFD for microencapsulation of probiotics 140
- 7.4 Advantages and limitations of SFD 144
- 7.5 Conclusion 144
- References 144
  
- 8 Optimization of Dairy Product Drying Processes 149**  
*S. Parthasarathi and C. Anandharamakrishnan*
- 8.1 Introduction 149
- 8.2 Experimental design tools for process optimization 149
- 8.2.1 Response surface methodology 149
- 8.2.1.1 Advantages of RSM 151
- 8.2.1.2 Limitations of RSM 151
- 8.2.2 Artificial neural networks 151
- 8.2.2.1 Feed-forward neural network 152
- 8.2.2.2 Learning process of an ANN 153
- 8.2.2.3 Optimization of process parameters 154
- 8.2.3 Finite element and finite volume methods 154
- 8.2.3.1 Finite element method 155
- 8.2.3.2 Finite volume method 155
- 8.3 Drying process variables and their influence on process and product quality 156
- 8.3.1 Drum drying 157
- 8.3.1.1 Heat and mass transfer 157
- 8.3.2 Spray drying 158
- 8.3.2.1 Exergy efficiency 160

- 8.3.2.2 Atomization 160
- 8.3.3 Freeze drying 161
- 8.3.3.1 Temperature measurement 162
- 8.3.3.2 Computational modelling 164
- 8.3.4 Spray freeze drying 169
- 8.4 Conclusion 170
- References 171

## **9 Computational Fluid Dynamics Modelling of the Dairy Drying Processes 179**

*J. Gimbut, W.P. Law and C. Anandharamakrishnan*

- 9.1 Introduction 179
- 9.2 Spray drying 179
- 9.2.1 Spray-drying process 179
- 9.2.2 Flow field simulation 180
- 9.2.2.1 Steady or unsteady approach 181
- 9.2.2.2 Turbulence modelling 182
- 9.2.3 Discrete phase modelling 183
- 9.2.4 Wall deposition and the particle build-up model 186
- 9.2.5 Particle interaction 186
- 9.2.6 Validation and issues of CFD simulation 189
- 9.3 Freeze drying 189
- 9.3.1 Modelling of freeze drying 190
- 9.3.1.1 Mass and heat-transfer modelling 190
- 9.3.1.2 Primary drying modelling 191
- 9.3.1.3 Secondary drying modelling 192
- 9.4 Spray freeze drying 193
- 9.5 Conclusions and future scope 196
- References 196

## **10 Physicochemical and Sensory Properties of Dried Dairy Products 203**

*P.H. Amaladhas and F. Magdaline Eljeeva Emerald*

- 10.1 Introduction 203
- 10.2 Milk Powder Manufacture 203
- 10.2.1 Roller drying 205
- 10.2.2 Spray drying 206
- 10.2.3 Freeze drying 208
- 10.2.4 Spray freeze drying 208
- 10.3 Properties of dairy powders as influenced by drying method 208
- 10.4 Physical properties 209
- 10.4.1 Morphology, particle size, shape and distribution 209
- 10.4.2 Density 210
- 10.4.3 Reconstitution properties 213
- 10.4.4 Agglomeration and instantization 216
- 10.4.5 Flowability and stickiness 216
- 10.4.6 Heat and coffee stability 217

- 10.5 Chemical and sensory properties 218
  - 10.5.1 Protein quality 218
  - 10.5.2 Non-enzymatic browning 219
  - 10.5.3 Oxidation and chemical quality 219
  - 10.5.4 Sensory quality 220
- 10.6 Properties of special powders 220
  - 10.6.1 Whey powders 220
  - 10.6.2 Whey protein concentrates 221
  - 10.6.3 Cheese powder 221
  - 10.6.4 Yoghurt powder 222
  - 10.6.5 Infant milk powders 222
  - 10.6.6 Dairy whiteners 223
- 10.7 Conclusion 223
- References 223
  
- 11 Packaging of Dried Dairy Products 229**  
*R. Gopirajah and C. Anandharamakrishnan*
  - 11.1 Introduction 229
  - 11.2 Dairy packaging trends 230
  - 11.3 Forms of packaging materials 231
    - 11.3.1 Metal cans 232
    - 11.3.2 Glass bottles 232
    - 11.3.3 Stretch-wrap packaging 232
    - 11.3.4 Flexible pouches 232
    - 11.3.5 Bag-in-box packages 233
    - 11.3.6 Cups 233
    - 11.3.7 Paper-board containers 233
  - 11.4 Packaging of dried milk products 234
    - 11.4.1 Packaging of whole milk powder 235
    - 11.4.2 Packaging of non-fat dried milk powder 236
  - 11.5 Developments in packaging techniques 237
    - 11.5.1 Intelligent packaging 237
    - 11.5.2 Active packaging 238
      - 11.5.2.1 Migration mechanism in active packaging 239
      - 11.5.2.2 The use of scavengers (absorbers) to prevent lipid oxidation 239
    - 11.5.3 Nanotechnology in dairy packaging 240
      - 11.5.3.1 Bionanocomposites and their applications 241
      - 11.5.3.2 Modelling the barrier properties of polymer-clay nanocomposites 242
  - 11.6 Conclusion 244
  - References 244
  
- 12 Recent Advances in the Drying of Dairy Products 249**  
*M.W. Woo*
  - 12.1 Introduction 249
  - 12.2 Typical layout of a dairy spray-drying process 250
    - 12.2.1 Multistage drying process 250
    - 12.2.2 Some unique process layouts 251

12.3	Advances in operating spray dryers	252
12.3.1	Controlling the drying process	252
12.3.1.1	Single droplet to dryer-wide prediction	252
12.3.2	Controlling powder stickiness and deposition	259
12.4	Advances in operating fluidized-bed dryers	261
12.4.1	Controlling crystallization	261
12.4.2	Controlling agglomeration	262
12.5	Conclusion	263
	References	263
<b>13</b>	<b>Industrial Scale Drying of Dairy Products</b>	<b>269</b>
	<i>D. Anand Paul</i>	
13.1	Introduction	269
13.2	Process flow in a dairy drying plant	270
13.3	Lexicon of industrial-scale drying	272
13.4	Industrial spray drying of dairy products	273
13.4.1	Automation of industrial-scale spray dryers	273
13.4.2	Efficiency of spray-dryer operation	274
13.4.3	Bottlenecks in industrial spray-drying	276
13.4.4	Hygiene in spray-dryer operation	277
13.4.5	Safety aspects of spray drying	278
13.5	Industrial drum drying of dairy products	279
13.5.1	Critical control points in industrial drum drying	280
13.5.2	Energy efficiency of drum drying	282
13.5.3	Safe operation of drum dryers	283
13.6	Conclusion	283
	References	283
<b>14</b>	<b>Challenges Involved in the Drying of Dairy Powders</b>	<b>287</b>
	<i>U. Kiran Kolli</i>	
14.1	Introduction	287
14.2	Challenges in the drying of dairy powders	288
14.2.1	Fouling	288
14.2.1.1	Mechanisms	288
14.2.1.2	Factors affecting fouling	289
14.2.2	Stickiness	291
14.2.3	Fires and explosions	292
14.2.4	Powder loss	293
14.2.5	Transport of powder	293
14.2.6	Storage of dairy powders	294
14.2.7	Plant economics	294
14.2.8	Development of speciality dairy powders	294
14.3	Use of modelling as a tool to solve some challenges	295
14.4	Conclusion	296
	References	296



## Contributors

### ***Aadinath***

Department of Food Engineering  
CSIR – Central Food Technological  
Research Institute  
Mysore, Karnataka, India

### ***P.H. Amaladhas***

Engineering Section  
National Dairy Research Institute  
Southern Campus  
Bangalore, Karnataka, India

### ***D. Anand Paul***

Nestle Research and Development Centre  
Manesar  
Gurgaon, India

### ***C. Anandharamakrishnan***

Indian Institute of Crop Processing  
Technology  
Ministry of Food Processing Industries  
Government of India  
Thanjavur, Tamil Nadu, India

### ***A. Bhushani***

Department of Food Engineering  
CSIR – Central Food Technological  
Research Institute  
Mysore, Karnataka, India

### ***N. Chhanwal***

Department of Food Engineering  
CSIR – Central Food Technological  
Research Institute  
Mysore, Karnataka, India

### ***Triroopa Ghosh***

Department of Food Engineering  
CSIR – Central Food Technological  
Research Institute  
Mysore, Karnataka, India

### ***J. Gim bun***

Centre of Excellence for Advanced  
Research in Fluid Flow  
Universiti Malaysia Pahang  
Gambang, Pahang, Malaysia

### ***R. Gopirajah***

Department of Food Engineering  
CSIR – Central Food Technological  
Research Institute  
Mysore, Karnataka, India

### ***P. Karthik***

Department of Food Engineering  
CSIR – Central Food Technological  
Research Institute  
Mysore, Karnataka, India

### ***U.K. Kollu***

ITC Limited  
Agri-Business Division  
Guntur, Andhra Pradesh, India

### ***W.P. Law***

Centre of Excellence for Advanced  
Research in Fluid Flow  
Universiti Malaysia Pahang  
Gambang, Pahang, Malaysia

***F. Magdaline Eljeeva Emerald***

Engineering Section  
National Dairy Research Institute  
Southern Campus  
Bangalore, Karnataka, India

***S. Padma Ishwarya***

Department of Food Engineering  
CSIR – Central Food Technological  
Research Institute  
Mysore, Karnataka, India

***S. Parthasarathi***

Department of Food Engineering  
CSIR – Central Food Technological  
Research Institute  
Mysore, Karnataka, India

***I. Roy***

Department of Food Engineering  
CSIR – Central Food Technological  
Research Institute  
Mysore, Karnataka, India

***A.G.F. Stapley***

Department of Chemical Engineering  
Loughborough University  
Loughborough, Leicestershire, UK

***M.W. Woo***

Department of Chemical Engineering  
Faculty of Engineering  
Monash University  
Clayton Campus, Victoria, Australia

## About the editor

**Dr C. Anandharamakrishnan** is currently the Director of Indian Institute of Crop Processing Technology, Thanjavur, Tamil Nadu, India. He obtained his doctorate in chemical engineering from Loughborough University, UK, for his work on experimental and computational fluid dynamics studies on spray freeze drying and spray drying of whey proteins. Formerly he was a Principal Scientist in the Department of Food Engineering at the CSIR – Central Food Technological Research Institute, Mysore, India. He specialises in the fields of drying, encapsulation of bioactive food ingredients and computational modelling of food processes. He has been actively involved in research on employing drying as an encapsulation technique for the protection and delivery of food bioactives, probiotics and flavours. He also has expertise in handling drying technology classes at the graduate and post graduate levels. Hitherto, he has published three books, and has nine patents and many research articles in international journals to his credit. He is the elected Fellow of the Royal Society of Chemistry (FRSC) and the Institute of Engineers (FIE) and is a recipient of several awards, including the Professor Jiwan Singh Sidhu Award 2010 from the Association of Food Scientists and Technologists (India).



## Preface

Drying, although it has its origin in prehistoric times, has paramount significance in the modern food processing industry. With respect to dairy processing, drying has certainly carved its own niche. Drying not only improves the shelf life and microbial quality of milk and milk products, but also makes them convenient for storage and transportation. Additionally, drying technology brings a variety of dried dairy products for the global consumer market alongside its vast applications in beverages, bakery and confectionery industries.

The subjects drying and dairy complement each other and are a developing field of research in both academia and industry. With enormous advances in drying techniques, any individual with expertise in the drying of dairy products can decipher new developments and improve their work. Hence, the *Handbook of Drying for Dairy Products* is an attempt to amalgamate the fundamental (theoretical) and technological (application) aspects of dairy-specific drying processes in a detailed fashion.

Drum drying and spray drying are the chief drying techniques used for dairy products. Apart from these, non-thermal processes such as freeze drying and the relatively modern spray freeze drying methods are applied for the preservation of starter cultures and the development of functional dairy ingredients. This book includes dedicated chapters for each of these techniques along with the characterization of dried powders and its packaging methods. Furthermore, industrial-scale drying of dairy products and its associated challenges are discussed in detail. Insights into the mathematical and computational tools adopted to optimize and predict the performance of drying process are also provided. Overall, this book showcases the significance of drying in the production of dairy powders and illustrates the further scope still existing in this vibrant technology.



## Acknowledgments

First and foremost, I would like to thank Professor Ram Rajasekharan, Director, CSIR – Central Food Technological Research Institute, Mysore, for his encouragement and able guidance for my academic endeavours. I also register thanks to my colleagues at the Indian Institute of Crop Processing Technology, Thanjavur, for their motivation.

I express my gratitude to Professor Chris Rielly and Dr Andy Stapley, Loughborough University, UK, for their constant support.

I thank all the chapter contributors and those involved at John Wiley & Sons Inc. for their work in bringing this book to fruition. My thanks also to Ms Anu Bhushani and all students of Computational Modelling and Nanoscale Processing Lab at CSIR–CFTRI, Mysore.



## 1

## Introduction to Drying

C. Anandharamakrishnan

*Indian Institute of Crop Processing Technology, Ministry of Food Processing Industries, Government of India,  
Thanjavur, Tamil Nadu, India*

### 1.1 Introduction

The history of drying dates back to 12000 BC, when people dried meat and fish under the sun. Since then, drying technology has evolved and it is presently an indispensable process in the industrial sector. Drying involves removal of relatively small proportions of volatile liquid from a product by thermal means via the vapour phase. With respect to food products, the volatile liquid is almost always water, present in bound or unbound form. Bound water is that which is physically and/or chemically entrapped within the microstructure of the food matrix; anything in excess of this is known as unbound water. In addition, the fraction of bound and unbound water that is removable at a given temperature is known as the free water content. The term *drying* is often used synonymously with *evaporation* and *dehydration*. However, it differs from evaporation in that the final product is a solid rather than a highly viscous liquid; it differs from dehydration in that the final moisture content of the dried food product is more than 2.5%, while that of dehydrated is less than 2.5% (Vega-Mercado *et al.* 2001).

Drying is one of the oldest methods of food preservation, resulting in shelf-stable products that are of utmost relevance in this era of convenience. The preservation effect is achieved by reducing the water content to a level that reduces the incidence of microbial growth and retards deteriorative chemical reactions such as enzymatic and non-enzymatic browning and rancidity due to lipid oxidation. Nevertheless, owing to the complex nature of foods, the effect of drying is not just limited to reduction in water content. The application of heat during drying causes structural modifications of macromolecular components in foods (carbohydrates, proteins and lipids), by which the final product acquires significant functional characteristics. Also, moisture diffusion from within the product is accompanied by various physical changes, including shrinkage, puffing, crystallization and glass transitions (Mujumdar 2007). Drying can also lead to the encapsulation of active components within a protective outer layer, owing to the difference in drying rate between the feed constituents. Spray drying of milk is a classical example of drying-mediated encapsulation wherein the fat component is encapsulated in the matrix of sugars and proteins. Apart from the above, drying enhances the transportation and packaging properties of food products,

attributed to the reduction in weight and volume. Before proceeding to understand the drying process, it is important to become familiar with the important terminologies associated with drying (Box 1.1).

#### Box 1.1 Lexicon of drying process

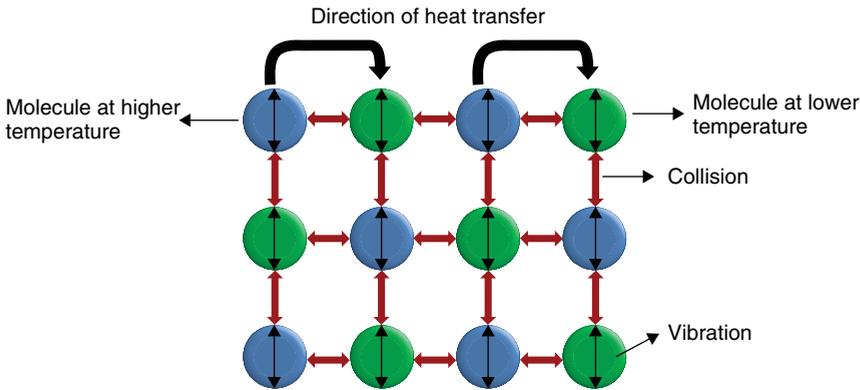
- **Critical moisture content:** The moisture content at which the drying rate starts to drop under constant drying conditions.
- **Equilibrium moisture content:** At a given temperature and pressure, the moisture content of a moist solid is in equilibrium with the gas–vapour mixture (zero for non-hygroscopic solids).
- **Bound moisture:** The amount of moisture tightly bound to the food matrix with properties different from those of bulk water; this also represents the portion of water that is unfreezable.
- **Unbound moisture:** Moisture in excess of the equilibrium moisture content, corresponding to saturated humidity.
- **Free moisture:** Amount of moisture mechanically entrapped in the void spaces of the system, having nearly all properties similar to those of bulk water.
- **Relative humidity:** Ratio of the partial pressure of water vapour in a gas–vapour mixture to equilibrium vapour pressure at the same temperature.
- **Water activity:** Relative humidity divided by 100.
- **Moisture sorption isotherm:** A graphical representation of the relationship between moisture content and equilibrium humidity (or) water activity at a specified temperature.
- **Dry bulb temperature:** Temperature measured by a (dry) thermometer immersed in a vapour–gas mixture.
- **Wet bulb temperature ( $T_{wb}$ ):** The liquid temperature attained when large amounts of air–vapour mixture is contacted with the surface. In purely convective drying, the drying surface reaches  $T_{wb}$  during the constant rate period.

## 1.2 Fundamental principles of drying: the concept of simultaneous heat and mass transfer

Drying is a simultaneous heat- and mass-transfer process. This is reasonable as the phase transition of any component is associated with the evolution of latent heat. In any process that involves a net transfer of mass from one phase to another, the heat-transfer rate is the limiting factor of the rate at which the mass is transferred (Foust *et al.* 2008).

### 1.2.1 Heat transfer during the drying process

Heat transfer occurs from the drying medium to the product surface and also from one point to another within the product. This is accomplished by one or a combination of the following mechanisms: conduction, convection, radiation and dielectric heating. These mechanisms vary with respect to the type of drying medium, mode of contact between the product and drying medium, and the scale of heat transfer within the product, that



**Figure 1.1** Principle of heating during conduction drying.

is, molecular or bulk transport, and the direction of heat transfer. However, irrespective of the above, the driving force for heat transfer is the temperature gradient that exists between the product and water surfaces at some location within the product (Singh & Heldman 2014). This can be appreciated from the equations governing heat transfer for each mechanism. The mode of heat transfer during drying also forms the basis of dryer classification, which is discussed in subsequent sections.

#### 1.2.1.1 Conduction drying

Conduction drying, also known as indirect or contact drying, occurs when heat is transferred to the product through contact with a metal surface that separates the product and the heating medium. Conduction heating involves transport of energy in a solid medium through vibration and collision of molecules and free electrons. The molecules vibrate by virtue of the heat energy absorbed from the drying medium. As a result, the molecules at higher temperature vibrate faster and transfer part of their kinetic energy to those at lower temperature by means of collision. However, only energy is transferred between the molecules and there is no change in their position.

A typical conduction dryer is made of a metal-walled, heat-jacketed arrangement that is either stationary or rotating. The jacketed vessel is heated by the circulation of condensed steam, flue gases, hot water, combustion gas, electricity or thermal fluids (e.g. silicone oil), which in turn transfers the heat to the metal surface of the dryer. Removal of vaporized water is independent of the heating medium. These dryers can operate in both batch and continuous modes. A drum dryer is a classical example of continuous conduction dryer, where the feed slurry is spread as a thin sheet over the surface of a rotating drum heated by steam. Heat transfer by conduction occurs from the heated drum to the sheet of feed slurry. The typical pattern of heat transfer in a conduction dryer is depicted in Figure 1.1.

The governing equation for heat transfer by conduction is given by *Fourier's law* (Eq. 1.1).

$$Q_{\text{conduction}} = kA \frac{(T_o - T_m)}{x} \quad (1.1)$$

where  $Q$  is the rate of heat transfer (W),  $k$  is the thermal conductivity (W/(m·K)),  $T_m$  is the surface temperature of the product, which is at or slightly above the boiling point of

water (K),  $T_o$  is the temperature of the drying medium (K),  $A$  is the area of heat transfer and  $x$  is the characteristic dimension of the product. The above equation is important as the rate of heat transfer has a significant influence on the extent of drying. There exists a positive correlation between heat-transfer rate and the temperature of the metal surface, but this is limited by the *case-hardening* phenomenon. Case hardening is the formation of surface shell during the early stages of drying, which is influenced by the temperature and velocity of drying medium (Chen 2008).

The thermal efficiency of conduction dryers is high as they consume only as much energy as is required to heat the product to its drying temperature. The operational temperature range is quite wide, from below the freezing point of water to close to the temperature of steam. This facilitates handling of products with different levels of heat sensitivity. Conduction dryers are also capable of operating under sub-atmospheric pressure and inert atmosphere. This enables the drying of food products that are susceptible to volatile loss and oxidation. Apart from drum dryers, other examples of conduction dryers include steam tube rotary dryers and cylinder dryers (continuous operation), vacuum tray dryers, freeze dryers and agitated pan dryers (batch operation) (Chakraverty & Singh 2014).

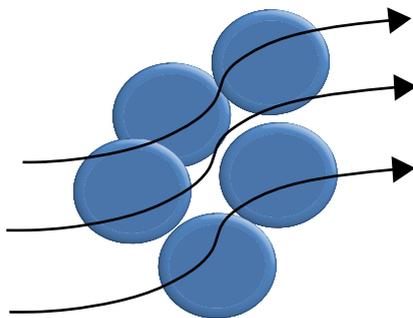
#### 1.2.1.2 Convection drying

In convection drying, also referred to as direct drying, heat transfer is accomplished by direct contact between the wet product and a stream of hot air (Das & Chakraverty 2003; Figure 1.2). On contrary to conduction, convection involves bulk heat transfer by movement of energy as eddies of currents inside a fluid. The molecules undergo displacement within the fluid as a function of their temperature and density. While the molecules at lower temperature are displaced downwards owing to their higher density, the opposite happens with those at higher temperature. In other words, molecules with lower kinetic energy replace the molecules with higher kinetic energy.

The rate of heat transfer by convection is given by:

$$Q_{\text{convection}} = \frac{hA}{\lambda}(T_o - T_m) \quad (1.2)$$

where  $h$  is the convective heat-transfer coefficient ( $\text{W}/\text{m}^2/\text{K}$ ) and  $\lambda$  is the latent heat of vaporization ( $\text{kJ}/\text{kg}$ ). The rate of heat transfer during convective drying is influenced by



**Figure 1.2** Principle of heating during convection drying.

Flow of heating medium past the solid product

the temperature, humidity, velocity and distribution pattern of the drying air and the product geometry and dimensions (Rahman & Perera 2007).

Convection drying is usually carried out as a continuous process in a closed chamber. Spray drying is a typical example of continuous convective drying, wherein the atomized feed droplets are dried by hot gas inside a spray chamber. Other examples of convective dryers include tray dryers, sheeting dryers, pneumatic convective dryers, rotary dryers, fluidized-bed dryers, tunnel dryers and compartment dryers. Convective drying is more energy intensive than conduction drying as the heat load is exerted by both the product and flow of the drying medium.

### 1.2.1.3 Radiation and dielectric drying

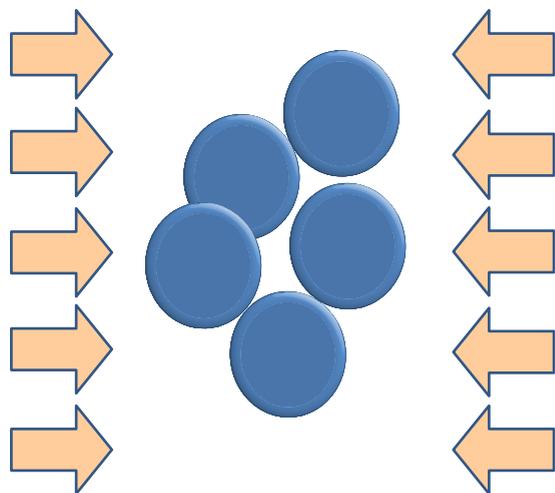
Radiation drying occurs when the product absorbs the radiant energy from a source and subsequently converts it into heat energy (Figure 1.3). There is no contact between the heated surface and the product, and this drying mode does not require a propagating medium. Solar drying is the most primitive form of radiation drying. The rate of heat transfer by radiation is given by the Stefan–Boltzmann law (Eq. 1.3):

$$Q_{\text{radiation}} = \varepsilon\sigma A(T_o^4 - T_m^4) \quad (1.3)$$

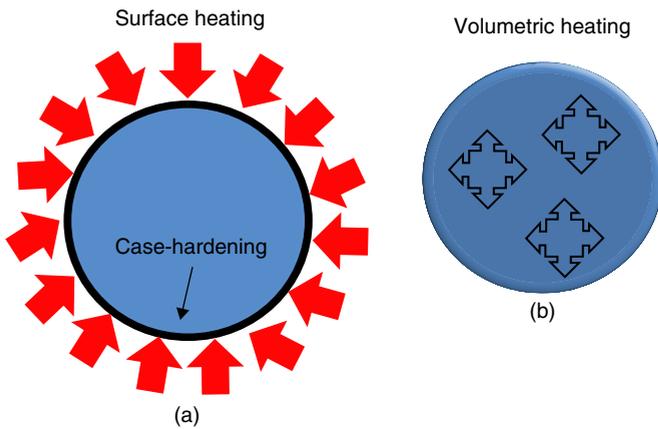
where  $\varepsilon$  is the emissivity of the product and  $\sigma$  is the Stefan–Boltzmann constant ( $5.670373 \times 10^{-8} \text{ W/m}^2/\text{K}^4$ ).

The concept of dielectric drying is a recent advancement with respect to the drying of food commodities, and comprises infra-red, microwave and radio-frequency drying methods. Here, the electromagnetic energy is selectively absorbed by the water present in a food product that undergoes volumetric heating. *Volumetric heating* refers to the generation and deposition of heat throughout the three-dimensional space within the product. This forms the primary difference to conventional drying, which is characterized by surface heating (outside-to-inside heating). The volumetric heating of dielectric drying overcomes the disadvantages of case hardening, which is associated with conventional drying (Figure 1.4). The surface heating caused by case hardening has a negative

**Figure 1.3** Principle of heating during radiation drying.



Absorption of radiant energy from the heating source



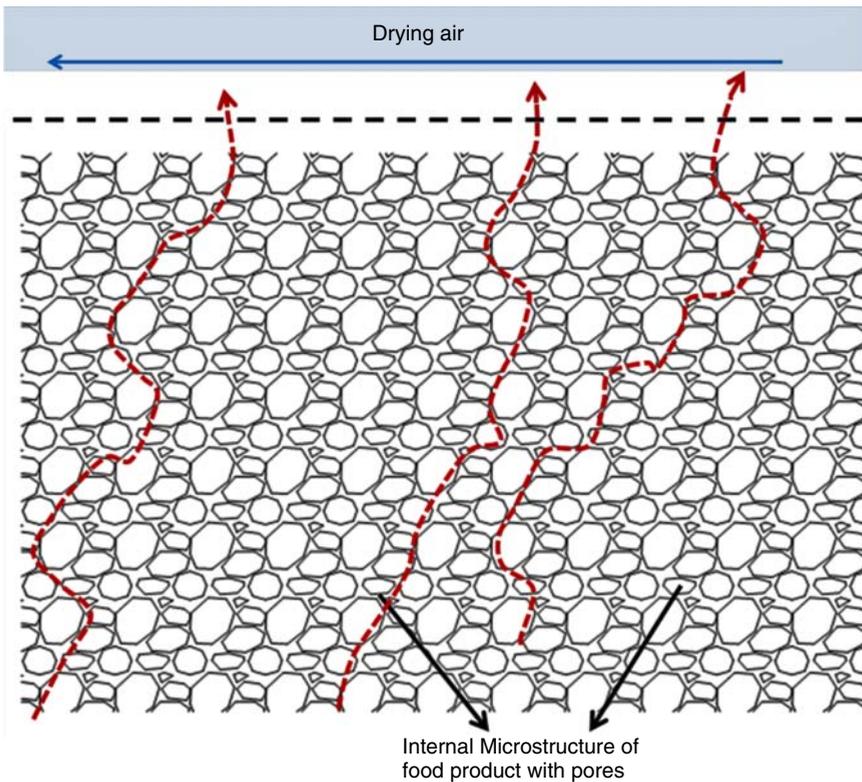
**Figure 1.4** Pattern of heating in (a) conventional and (b) dielectric drying.

impact on both drying efficiency and product quality (Chakraverty & Singh 2014). Consequently, dielectric drying leads to higher thermal efficiency and shorter drying time. Furthermore, the selective and speedy energy absorption by water facilitates its rapid evaporation by the outward flux of water vapour. The outcomes are prevention of shrinkage and collapse in microstructure, leading to improved rehydration properties of the dried product. The dielectric drying methods are often employed at the end of the process lines to remove the residual moisture content of the final product.

### 1.2.2 Mass transfer during the drying process

The transfer of mass, in this case the moisture content, takes place from one phase to another, involving transitions among the solid, liquid and gaseous states. In most cases, drying is accomplished through evaporation-mediated phase transition of water from the liquid state to the vapour state by the addition of the latent heat of vaporization. Heat supplied by the drying medium is utilized to counterbalance the considerably large latent heat of vaporization for water (2200 kJ/kg). This increases the energy requirement of drying process. However, the withdrawal of latent heat from the drying medium maintains the product at relatively low temperature, more precisely at the wet-bulb temperature. The wet-bulb temperature ( $T_{wb}$ ) is the temperature of air when it reaches 100% relative humidity, as water evaporates into it due to the supply of latent heat by the drying medium.  $T_{wb}$  is the lowest temperature that can be reached under ambient conditions by the evaporation of water. In certain exceptional cases, drying occurs by sublimation of the solid phase directly into the vapour phase, via the addition of latent heat of fusion (Mujumdar 2007). The removal of liquid water or water vapour from within the product to the surrounding medium follows a tortuous pathway (Figure 1.5) that is unique for each food product as a result of the structural changes that occur during the drying. The mechanisms that govern the transport of liquid water and water vapour are elaborated with respect to different drying stages in the subsequent sections.

From the above discussion, it is clear that the transport processes occur both within the product and also between the product and the drying medium. While the former is diffusion controlled due to the tortuous pathway that results during the later stages of drying, the latter is a function of the free moisture content at the surface. The limiting



**Figure 1.5** Tortuous pathway for moisture removal during drying.

parameter is the water activity ( $a_w$ ), which presents the gradient for water movement and an equilibrium condition that marks the end point of the drying process. Water activity can be defined as the ratio of the vapour pressure of the solution to that of the solvent (water). In other words,  $a_w$  is equilibrium relative humidity divided by 100. This justifies the use of high temperature in most of drying methods, as higher temperatures result in lower equilibrium moisture content and hence present a larger concentration gradient for moisture removal (Singh & Heldman 2014).

The mass transport of water can occur in two ways: liquid water can be transported to the surface and then removed as vapour by evaporation or it can be evaporated within the product at the liquid–vapour interface and transported as vapour to the surface. Thus, different transport mechanisms have been elucidated for liquid and vapour transport. The two major mechanisms of mass transport are described below.

#### 1.2.2.1 Diffusion mechanism

The driving force for mass transfer by diffusion is obtained by the difference in partial pressure or concentration that prevails between the product surface and the surrounding unsaturated gas phase. In addition to the pressure or concentration gradient, mass transfer is also dependent on the system properties, represented by the mass-transfer coefficient. This is analogous to the heat-transfer coefficient in the heat-transport

process. The governing equation for mass transfer by diffusion is given by Fick's second law (Eq. 1.4):

$$\frac{dx}{dt} = D_{\text{eff}} \frac{\partial^2 x}{\partial l^2} \quad (1.4)$$

where,  $x$  is the moisture content of the product (kg H<sub>2</sub>O/kg product),  $t$  is time (s),  $l$  is the distance in the direction of mass transfer ( $m$ ) and  $D_{\text{eff}}$  is the diffusion coefficient or moisture diffusivity (m<sup>2</sup>/s).

Equation (1.4) is analogous to the Fourier equation of heat transfer (Eq. 1.1), but with temperature and thermal diffusivity replaced with concentration and moisture diffusivity, respectively. The diffusivity increases with an increase in the drying air temperature, defined by the Arrhenius relationship (Eq. 1.5):

$$D_{\text{eff}} = D_o \exp\left(\frac{-E_o}{RT}\right) \quad (1.5)$$

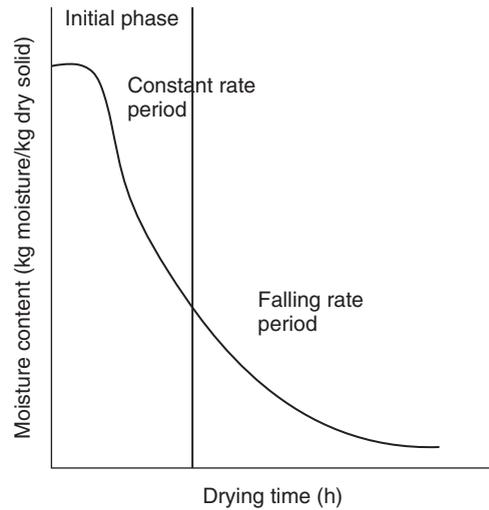
where  $D_o$  is the pre-exponent factor (m<sup>2</sup>/s),  $E_o$  is the activation energy for moisture diffusion (kJ/mol),  $R$  is the ideal gas constant (kJ/(mol·K)) and  $T$  is the absolute temperature (K). In addition, diffusivity is also found to decrease with decreasing moisture content as the drying proceeds. The diffusion mechanism of mass transfer is observed during the removal of residual moisture from products such as flour and starch and also in other non-porous solids (Geankoplis 2006) during the latter stages of drying.

The diffusion can be that of liquid water or water vapour, with osmotic pressure and partial pressure as the driving forces, respectively. Liquid diffusion is limited by the attainment of equilibrium moisture content. The difference in total pressure produced by external pressure and temperature also aids in liquid or vapour transport. This is governed by Poiseuille's law, which explains the laminar flow of an incompressible and Newtonian fluid flowing through a long cylindrical pipe of constant cross-section, mediated by difference in pressure. In addition to the concentration and pressure gradient, the internal microstructure of product also plays a significant role in diffusion transport. According to the pore size, two types of diffusion mechanisms can be defined: Knudsen and mutual diffusion. The former mechanism occurs at low pressure in products with small pores of size less than the mean free path of the molecules and when the frequency of molecular collision with the walls is predominant over inter-molecular collision. Vapour transport by Knudsen diffusion is a function of vapour density, Knudsen diffusivity, size and number of pores, tortuosity, and characteristic dimension of the product. The latter type of diffusion occurs when the pore size is larger than the free path of diffusion of vapour molecules.

#### 1.2.2.2 Capillary mechanism

Capillary forces are known to act in synergy with the diffusion mechanism to facilitate the drying of food products (Gorling 1956, 1958). In this mechanism, the moisture movement is arbitrated by surface tension rather than diffusion. The porous microstructure of the product plays a key role here. The interconnected pores communicate with the external surface by means of channels through which the moisture is removed. The water removal is accompanied by the formation of a meniscus across each pore and subsequent setting of interfacial tension at the solid–water boundary. This initiates the development of capillary forces at the interface in a direction perpendicular to the solid

**Figure 1.6** Typical drying curve.



surface. Thus, these capillary forces act as the driving force for moisture movement from within the porous structure of the product to the surface. However, the pore size plays an influential role, with the smaller pores leading to greater capillary forces than the larger ones (Geankoplis 2006). Capillary forces can be enhanced by the use of surfactants that reduce the surface tension of water (Rahman & Perera 2007).

### 1.3 The drying curve

Every product exhibits a typical curve that indicates its drying characteristics under specific conditions of the temperature, pressure, and velocity of the drying medium. Thus, it is evident that the dry-bulb and wet-bulb temperatures of the drying air play a vital role in determining the characteristic curve of a particular product. This is known as the drying curve, a plot of product moisture content versus drying time (Figure 1.6). The drying curve shows three distinct stages, which are described in the following section.

### 1.4 Stages of drying

Drying occurs in three stages: a short initial phase followed by the constant rate and falling rate drying periods. During the initial phase, the product heats up from the ambient temperature ( $T_a$ ) to the evaporation temperature ( $T_e$ ). In other words, the product temperature alters until it reaches a steady state. The solid temperature and the rate of drying may increase or decrease to reach the steady-state condition. When the product temperature is equal to the wet-bulb temperature of gas, the drying rate remains constant. This marks the beginning of the constant rate drying period (Foust *et al.* 2008). A comprehensible representation of the drying stages is given by the drying rate curve, which is a plot of free moisture content versus drying rate (Figure 1.7).

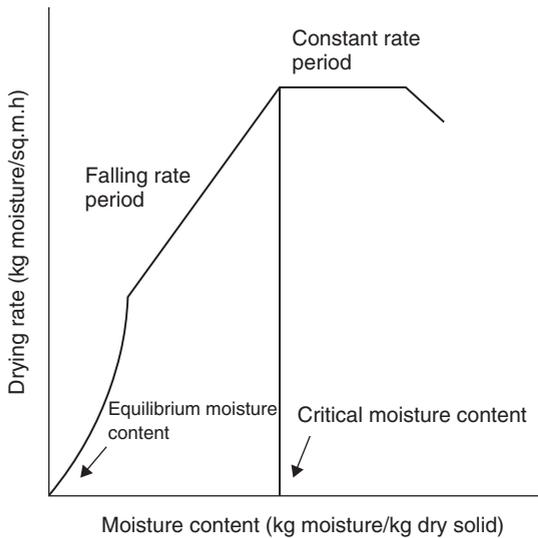


Figure 1.7 Drying rate curve.

#### 1.4.1 Constant rate period

After the product attains its steady state, there is an initial linear reduction in the moisture content as a function of time, known as the constant drying rate period (Figures 1.6 and 1.7). During this period, as the name implies, the rate of water movement from within the food is equal to the rate at which the water evaporates from the surface. This stage is externally mass-transfer controlled while the surface is always wet. This is because there is a thin film of water at the product surface and no internal or external mass-transfer resistance (Rahman & Perera 2007). Thus, this stage predominantly involves the removal of free moisture that is available in the product at specific humidity and temperature. Because of the continuous replenishment of moisture, the surface essentially remains at the wet-bulb temperature of drying air. This can be ascribed to the phenomenon of *evaporative cooling*, by which the water film formed at the product surface as a result of adiabatic evaporation with the hot drying medium remains at the wet-bulb temperature of the drying gas.

The constant rate drying period proceeds as long as the surface remains wet and until the critical moisture content ( $M_c$ ) is reached. During the constant rate period, the drying rate depends on the temperature, moisture content and mass flow of air. Overall, the drying rate during the constant rate period is considered to be heat-transfer limited.

Calculation of the drying rate during the constant rate period is based on the equilibrium that exists between rate of heat transfer and mass transfer (as moisture loss) between the food product and the surrounding drying medium. The rate of heat transfer is given by Eq. (1.2). Similarly, the mass-transfer rate is given by:

$$\frac{\partial M}{\partial t} = KA(H_s - H_a) \quad (1.6)$$

where  $\frac{\partial M}{\partial t}$  is the rate of mass transfer or drying (kg/s),  $K$  is the mass-transfer coefficient (kg/(m<sup>2</sup>·s)),  $A$  is the surface area for drying (m<sup>2</sup>), and  $H_s$  and  $H_a$  (kg moisture/kg air) are

the humidity of the product surface and drying medium, respectively. At equilibrium, the rate of moisture removal at constant product volume is given by:

$$\frac{\partial M}{\partial t} = \frac{hA}{\lambda}(T_o - T_m) \quad (1.7)$$

where  $h$  is the heat-transfer coefficient ( $\text{W}/\text{m}^2/\text{k}$ ). Integration of Eq. (1.7) yields the expression for calculation of the duration of the constant rate drying period:

$$t = \frac{A\lambda}{h} \left( \frac{M_o - M_c}{T_o - T_m} \right) \quad (1.8)$$

where  $M_o$  and  $M_c$  are the initial moisture content and critical moisture content ( $\text{kg}$  water/ $\text{kg}$  dry product), respectively.

#### 1.4.2 Falling rate period

Below  $M_c$ , the moisture content continues to decrease, but at a lower rate, since the mass transfer becomes internally mass-transfer controlled and diffusion governed. The surface of the product dries up and the temperature of the product rises close to the dry-bulb temperature of the air. At high moisture content, liquid flow due to capillary forces dominates. However, at decreasing moisture content, the amount of liquid in the pores decreases and a gas phase is built up, causing a decrease in liquid permeability. Gradually, the mass transfer is taken over by vapour diffusion in a porous structure (Rahman & Perera 2007). At saturation point, liquid is no longer available in the pores and mass transfer is taken over completely by vapour diffusion (Coumans & Kruf 1994). Thus, collectively, there is a decrease in the driving forces for heat and mass transfer. The transport processes cease to occur when the product temperature is nearly equal to the air temperature and the moisture content is equal to the equilibrium moisture content. Further drying of the product is not possible under ideal conditions. However, experimental determination of this end point or the state of equilibrium is tedious. The falling rate period takes a comparatively longer time than the constant rate period, although the amount of moisture removal is less. Thus, the product temperature and internal mass transfer are the rate-limiting factors during the falling rate period.

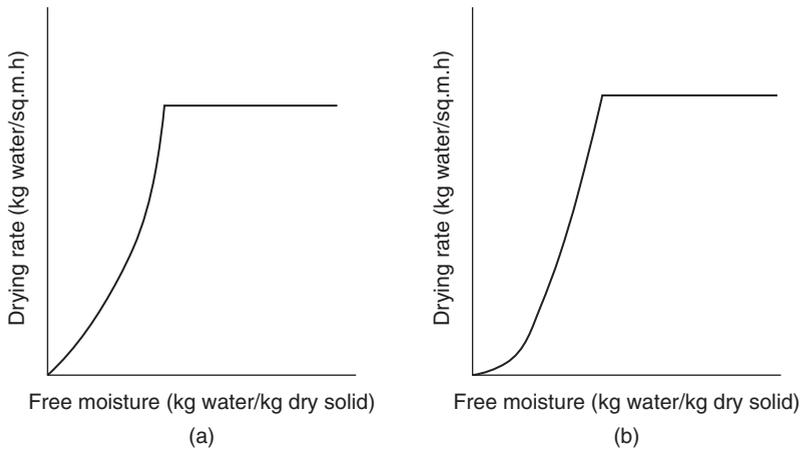
The critical moisture content at which the transition occurs from the constant to falling rate period varies with the food product. In general, it occurs at 58–65% of the equilibrium relative humidity of air, but most foods depict only a pseudo constant rate period with a steadily dropping drying rate. This indicates that food products predominantly undergo drying during the falling rate period.

The time for the falling rate period is given by:

$$t = \frac{D\pi^2}{4L^2} \ln \left( \frac{M_c - M_e}{M_f - M_e} \right) \quad (1.9)$$

where  $L$  is the characteristic dimension of the product,  $D$  is the diffusivity ( $\text{m}^2/\text{h}$ ), and  $M_e$  and  $M_f$  are the equilibrium and final moisture contents, respectively. While the above equation is governed by the diffusion mechanism, that governed by the capillary flow of moisture is:

$$t = \frac{\rho L \lambda (M_c - M_e)}{h(T_o - T_m)} \ln \left( \frac{M_c - M_e}{M_f - M_e} \right) \quad (1.10)$$



**Figure 1.8** Drying rate curve with (a) diffusion mechanism and (b) capillary mechanism. Redrawn from Geankoplis (2006).

Two distinct falling rate periods may occur, depending on the product structure and drying conditions. A significant observation is that the falling rate period has a significant dependency on the mechanism of mass transfer. This is portrayed by the difference in drying rate curves resulting from drying processes governed by diffusion or capillary forces. In diffusion, the initial constant rate drying is predominant such that the first falling rate period comprising unsaturated surface evaporation does not occur (Figure 1.8a). With capillary force, the fine pores in the product cause the portion of the drying rate curve corresponding to the second falling rate period to turn upward (Figure 1.8b) (Geankoplis 2006).

## 1.5 Techniques for the drying of dairy products

Dried milk products are one of the major categories of tradable dairy commodities. The value addition of milk by means of drying is relevant owing to the perishable nature of liquid milk. Apart from enhanced shelf-life, as mentioned at the beginning of this chapter, drying of milk is also considered to be an effective marketing strategy as it reduces the bulkiness of the product and increases sensory appeal. This is the driving force behind a series of innovations in dairy drying techniques since they began in the 13th century. As with other food products, sun drying was initially used for milk. Industrial-scale drying of milk commenced only in the 19th century. The first dried milk was in the form of pills that were obtained after open-vessel evaporation, followed by air drying to remove the residual moisture (Olson 1950).

The full-fledged manufacture of dried milk powder began when spray-drying and drum-drying equipment was developed in 1872 and 1902, respectively. Since then the drying technology for milk products has undergone continuous evolution. It has included numerous innovations, such as the development of multiple-stage drying techniques for instantization and energy efficiency (Caric & Kalab 1987), and low-temperature drying techniques like freeze drying for enhanced quality of