Edited by Evangelos Tsotsas
and Arun S. Mujumdar

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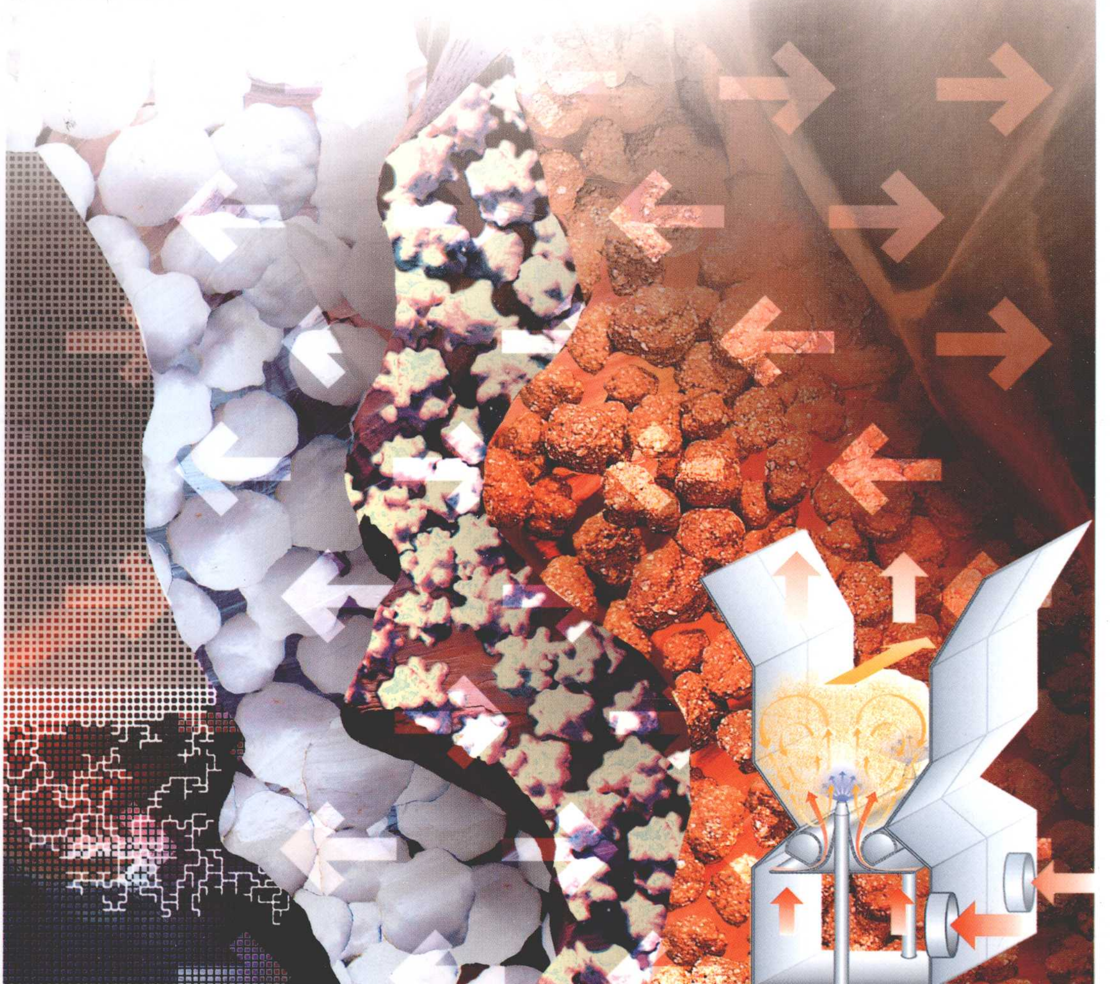
Modern Drying Technology

Energy Savings

Volume 4



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Volume 4: Energy Savings

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Other Volumes

Volume 1: Computational Tools at Different Scales

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Forthcoming Volumes

Volume 5: Process Intensification

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Modern Drying Technology Set (Volumes 1 – 5)

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Series Preface

The present series is dedicated to drying, that is, to the process of removing moisture from solids. Drying has been conducted empirically since the dawn of the human race. In traditional scientific terms it is a unit operation in chemical engineering. The reason for the continuing interest in drying and, hence, the motivation for the series concerns the challenges and opportunities. A permanent challenge is connected to the sheer amount and value of products that must be dried – either to attain their functionalities, or because moisture would damage the material during subsequent processing and storage, or simply because customers are not willing to pay for water. This comprises almost every material used in solid form, from foods to pharmaceuticals, from minerals to detergents, from polymers to paper. Raw materials and commodities with a low price per kilogram, but with extremely high production rates, and also highly formulated, rather rare but very expensive specialties have to be dried.

This permanent demand is accompanied by the challenge of sustainable development providing welfare, or at least a decent living standard, to a still-growing humanity. On the other hand, opportunities emerge for drying, as well as for any other aspect of science or living, from either the incremental or disruptive development of available tools. This duality is reflected in the structure of the book series, which is planned for five volumes in total, namely:

Volume 1: Computational tools at different scales
Volume 2: Experimental techniques
Volume 3: Product quality and formulation
Volume 4: Energy savings
Volume 5: Process intensification

As the titles indicate, we start with the opportunities in terms of modern computational and experimental tools in Volumes 1 and 2, respectively. How these opportunities can be used in fulfilling the challenges, in creating better and new products, in reducing the consumption of energy, in significantly improving existing or introducing new processes will be discussed in Volumes 3, 4 and 5. In this sense, the first two volumes of the series will be driven by science; the last three will try to show how engineering science and technology can be translated into progress.

In total, the series is designed to have both common aspects with and essential differences from an extended textbook or a handbook. Textbooks and handbooks usually refer to well-established knowledge, prepared and organized either for learning or for application in practice, respectively. On the contrary, the ambition of the present series is to move at the frontier of "modern drying technology", describing things that have recently emerged, mapping things that are about to emerge, and also anticipating some things that may or should emerge in the near future. Consequently, the series is much closer to research than textbooks or handbooks can be. On the other hand, it was never intended as an anthology of research papers or keynotes – this segment being well covered by periodicals and conference proceedings. Therefore, our continuing effort will be to stay as close as possible to a textbook in terms of understandable presentation, and as close as possible to a handbook in terms of applicability.

Another feature in common with an extended textbook or a handbook is the rather complete coverage of the topic by the entire series. Certainly, not every volume or chapter will be equally interesting for every reader, but we do hope that several chapters and volumes will be of value for graduate students, for researchers who are young in age or thinking, and for practitioners from industries that are manufacturing or using drying equipment. We also hope that the readers and owners of the entire series will have a comprehensive access not to all, but to many significant recent advances in drying science and technology. Such readers will quickly realize that modern drying technology is quite interdisciplinary, profiting greatly from other branches of engineering and science. In the opposite direction, not only chemical engineers, but also people from food, mechanical, environmental or medical engineering, material science, applied chemistry or physics, computing and mathematics may find one or the other interesting and useful results or ideas in the series.

The mentioned interdisciplinary approach implies that drying experts are keen to abandon the traditional chemical engineering concept of unit operations for the sake of a less rigid and more creative canon. However, they have difficulties of identification with just one of the two new major trends in chemical engineering, namely process-systems engineering or product engineering. Efficient drying can be completely valueless in a process system that is not efficiently tuned as a whole, while efficient processing is certainly valueless if it does not fulfill the demands of the market (the customer) regarding the properties of the product. There are few topics more appropriate in order to demonstrate the necessity of simultaneous treatment of product and process quality than drying. The series will try to work out chances that emerge from this crossroads position.

One further objective is to motivate readers in putting together modules (chapters from different volumes) relevant to their interests, creating in this manner individual, task-oriented threads through the series. An example of one such thematic thread set by the editors refers to simultaneous particle formation and drying, with a focus on spray fluidized beds. From the point of view of process-systems engineering, this is process integration – several "unit operations" take place in the same equipment. On the other hand, it is product engineering, creating structures – in many cases nanostructures – that correlate with the desired application properties. Such properties are distributed over the ensemble (population) of particles, so that it is necessary to discuss mathematical methods (population balances) and numerical tools able to resolve the respective distributions in one chapter of Volume 1. Measuring techniques providing access to properties and states of the particle system will be treated in one chapter of Volume 2. In Volume 3, we will attempt to combine the previously introduced theoretical and experimental tools with the goal of product design. Finally, important issues of energy consumption and process intensification will appear in chapters of Volumes 4 and 5. Our hope is that some thematic combinations we have not even thought about in our choice of contents will arise in a similar way.

As the present series is a series of edited books, it cannot be as uniform in either writing style or notation as good textbooks are. In the case of notation, a list of symbols has been developed and will be printed at the beginning of every volume. This list is not rigid but foresees options, at least partially accounting for the habits in different parts of the world. It has been recently adopted as a recommendation by the Working Party on Drying of the European Federation of Chemical Engineering (EFCE). However, the opportunity of placing short lists of additional or deviant symbols at the end of every chapter has been given to all authors. The symbols used are also explained in the text of every chapter, so that we do not expect any serious difficulties in reading and understanding.

The above indicates that the clear priority in the edited series was not in uniformity of style, but in the quality of the contents that are very close to current international research from academia and, where possible, also from industry. Not every potentially interesting topic is included in the series, and not every excellent researcher working on drying contributes to it. However, we are very confident about the excellence of all research groups that we were able to gather together, and we are very grateful for the good cooperation with all chapter authors. The quality of the series as a whole is set mainly by them; the success of the series will primarily be theirs. We would also like to express our acknowledgements to the team of Wiley-VCH who have done a great job in supporting the series from the first idea to realization. Furthermore, our thanks go to Mrs Nicolle Degen for her additional work, and to our families for their tolerance and continuing support.

Last but not least, we are grateful to the members of the Working Party on Drying of the EFCE for various reasons. First, the idea for the series came up during the annual technical and business meeting of the working party 2005 in Paris. Secondly, many chapter authors could be recruited among its members. Finally, the Working Party continues to serve as a panel for discussion, checking and readjustment of our conceptions about the series. The list of the members of the working party with their affiliations is included in every volume of the series in the sense of acknowledgment, but also in order to promote networking and to provide access to national working parties, groups and individuals. The present edited books are complementary to the regular activities of the EFCE Working Party on Drying, as they are also complementary to various other regular activities of the international drying community, including well-known periodicals, handbooks, and the International Drying Symposia.

December 2006

Evangelos Tsotsas
Arun S. Mujumdar

Preface of Volume 4

As already stressed in the general preface, the contents of modern drying technology are subjected to the dual requirement of producing high-quality products with highly efficient processes. Moreover, drying is energetically expensive – a major consumer of energy in modern societies – which makes energy use a crucial aspect of process efficiency. In times of abundant and inexpensive energy, one might ignore – and many people did – the respective consumption, concluding that any drying process is a good process as long as the desired product properties can be preserved or established. However, cheap energy seems to belong to history, and serious environmental concerns have appeared, related to climate change. Consequently, modern drying technology must address the complete challenge, regarding product quality and process efficiency as the two faces of the same coin, and treat them concurrently. Having discussed "Product quality and formulation" in Volume 3 of this series, we turn our attention to "Energy savings" in Volume 4. The optimistic title should by no means conceal difficulties arising from thermodynamic and economic restraints, but it does express our confidence that modern drying technology can fulfill the task. This confidence stems from a number of available methods, emerging approaches and innovative ideas, which can seriously serve and significantly contribute to the ultimate goal of energetically efficient drying processes, as presented in the following eight chapters:

Chapter 1: Fundamentals of energy analysis of dryers
Chapter 2: Mechanical solid-liquid separation processes and techniques
Chapter 3: Energy considerations in osmotic dehydration
Chapter 4: Heat pump assisted drying technology – Overview with focus on energy, environment and product quality
Chapter 5: Zeolites for reducing drying energy usage
Chapter 6: Solar drying
Chapter 7: Energy issues of drying and heat treatment for solid wood and other biomass sources
Chapter 8: Efficient sludge thermal processing: From drying to thermal valorization

Chapter 1 sets the fundamentals of energy analysis, breaking down the total energy consumption of a dryer in its constituent parts, defining efficiency, and identifying sources and reasons for inefficiency and losses. Pinch analysis is discussed in detail as a powerful tool for assessing the potential of and designing heat transfer from hot to cold material streams. Various other methods that can lead to energy savings are classified and presented – from altering operating conditions to the combination of heat and power. Specific examples that range from learning exercises to industrial case studies are used to put figures and numbers behind the principles. Most important, Chapter 1 points out very clearly that dryer energy savings should always be considered in the context of the overall process or even production cite, in a systemic approach.

An evident systemic aspect is that the energy consumption of any dryer decreases with decreasing moisture content in the feed. Unfortunately, the respective potential for energy savings is not always fully utilized, because thermal drying and the preceding solid-liquid separation are designed separately, often by different people. Therefore, solid-liquid separation processes are highlighted in Chapter 2, including an exhaustive taxonomy, the detailed presentation of equipment, and criteria for selection and design. Modern techniques for the enhancement of such separations by electric or magnetic forces are presented. Furthermore, improvements that can be attained by the consecutive, parallel or combined use of equipment are discussed, referring to both purely mechanical steps and to the combination of mechanical separation with thermal drying in the batch or continuous mode of operation.

Another possibility to remove water out of soft materials previously to drying, namely osmosis, is treated in Chapter 3. Osmotic dehydration is relevant to food processing and can lead to significant energy savings in the drying step, but it has also an impact on food quality, which must be simultaneously considered. Experiences with and benefits from the combination of osmotic dehydration with different kinds of thermal drying are comprehensively reviewed.

One major source of energy loss from conventional one-pass hot-air dryers is "over the chimney". Therefore, heat recovery from the warm and moist exhaust air is a key to the enhancement of the energetic efficiency of dryers. Since such recovery can be achieved by heat pumps, heat pump drying is discussed in detail in Chapter 4. A distinctive advantage of this technology lies in its add-on character – it can be applied to virtually any kind of dryer, though it is most reasonable in combination with low to moderate temperature dryers for the processing of sensible goods. Chapter 4 explains the principles of different types of heat pumps, presents various methods for their combination with dryers, and quantifies the merits that can be obtained in terms of improved energetic efficiency. Extensive records of successful application to various products – food and agricultural, wood and timber, pharmaceutical and biological – are presented, design methods are discussed, and opportunities for future development are outlined.

Similarly to heat pumps, particulate adsorbents – especially zeolites – can also be used for heat recovery from dryer exhaust gases. Zeolite drying is highlighted as a powerful and promising technology in Chapter 5. It is pointed out that zeolites can be used for heat recovery from the exhaust, but they can also serve the purpose of inlet air dehumidification, or even be mixed to and subsequently separated from the drying material. The resulting energy savings are evaluated in a systematic way, starting with simple configurations and moving step-by-step to more complex multi-stage or steam-operated systems. Examples of already realized facilities for the drying of dairy products, sludge and seeds are presented. Finally, economic aspects are analyzed in terms of pay-back times for the necessary additional investment.

In Chapter 6, solar drying is treated as a further energetically promising alternative. Solar energy is for free, but reaches the Earth with a relatively low flux and a strongly fluctuating rate. To use it for drying, solar energy must be harvested in an efficient way that does not require too much additional investment. This leads to special constructions of solar collectors and dryers, which are classified and discussed in detail. Applications of such equipment are presented for various agricultural products, and the necessity for relaxing the influence of variable energy input by appropriate control strategies is stressed. Case studies on timber and tobacco are used to show that solar drying can be economically viable and beneficial in comparison to both, primitive sun drying but also conventional hot-air drying.

It is well known that the harvesting of solar energy is very efficiently carried out by plants, creating biomass. Some kinds of biomass, namely wood, can be used to, for example, make furniture, some others as renewable fuels. Since both applications are closely related to drying and of a very large scale, they are discussed thoroughly in Chapter 7. First, benchmarks are provided for the energy demand of wood drying kilns, and methods for saving energy by improved kiln design and operation are presented. It is, then, shown, that preconditioning by drying can enhance the efficiency of processes aiming at the energetic valorization of biomass, such as combustion or gasification. Various drying technologies for fuel biomass are discussed. Dual-scale models applicable to the drying of both, timber pieces and fuel biomass particles are presented. Apart from the assessment of energetic efficiency, such models can also track product quality in terms of, for example, timber distortion or uniformity of residual moisture in a fuel biomass particle system.

Finally, Chapter 8 addresses the energetic issues of one more large-scale application of drying, namely the drying of sludge from wastewater treatment facilities. The case is similar to woody biomass, because the main component of sludge is bacterial biomass that may just need to be dried before, for example, landfill, or may require drying in combination with subsequent processes of thermal valorization, such as – again – combustion or gasification. After a presentation of sludge composition and properties, the various types of drying equipment and processes that can be used for sludge are discussed thoroughly, along with their energetic efficiency. Specific case studies illustrate that the proper integration of drying in municipal wastewater treatment plants can significantly reduce the energy demand, and that sludge can have a significant value as a fuel, if efficiently pre-dried.

Due to nature of the topic, the present volume of Modern Drying Technology has interdisciplinary links to thermodynamics, energy and environmental engineering, process systems engineering, food engineering, meteorology, forestry, biology and biotechnology, but also to economics. Concerning the scale, single particles and processing equipment (particle systems) are considered, but also entire production sites and global environmental and economic systems.

Thematic threads within the Modern Drying Technology series exist from the present:

- Chapter 1 to Chapter 7 of Vol. 1 (systems engineering)
- Chapters 2 and 5 to Chapter 6 of Vol. 2 (particle characterization)
- Chapters 3 and 4 to Chapters 1 and 2 of Vol. 3 (food processing)
- Chapter 7 to Chapter 1 of Vol. 1 (wood drying)
- Chapter 8 to Chapters 4 of Vol. 2 and Chapter 5 of Vol. 3 (gel materials)

Additionally, the entire present volume is closely related to Vol. 3, as the already mentioned two faces of the same coin. The overall message is that of drying science and technology in good shape for doing exactly what the title of the volume describes, namely saving energy.

Acknowledgements for Volume 4 are the same as in the series preface, we would like to stress them by reference, but not repeat them here.

August 2011

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Recommended Notation

- Alternative symbols are given in brackets
- Vectors are denoted by bold symbols, a single bar, an arrow or an index (e.g., index: i)
- Tensors are denoted by bold symbols, a double bar or a double index (e.g., index: i, j)
- Multiple subscripts should be separated by colon (e.g., $\rho_{p,dry}$: density of dry particle)

A	surface area	m^2
a_w	water activity	–
B	nucleation rate	$kg^{-1}\ m^{-1}\ s^{-1}$
b	breakage function	m^{-3}
$C(K)$	constant or coefficient	various
c	specific heat capacity	$J\ kg^{-1}\ K^{-1}$
D	equipment diameter	m
$D(\delta)$	diffusion coefficient	$m^2\ s^{-1}$
d	diameter or size of solids	m
E	energy	J
F	mass flux function	–
$F(\dot{V})$	volumetric flow rate	$m^3\ s^{-1}$
f	relative (normalized) drying rate	–
f	multidimensional number density	–
G	shear function or modulus	Pa
G	growth rate	$kg\ s^{-1}$
g	acceleration due to gravity	$m\ s^{-2}$
H	height	m
H	enthalpy	J
H	Heaviside step function	–
h	specific enthalpy (dry basis)	$J\ kg^{-1}$
$h(\alpha)$	heat-transfer coefficient	$W\ m^{-2}\ K^{-1}$
$\tilde{h}(h_N)$	molar enthalpy	$J\ mol^{-1}$
Δh_v	specific enthalpy of evaporation	$J\ kg^{-1}$
I	total number of intervals	–