Modelling Drying Processes

This comprehensive summary of the state-of-the-art and the ideas behind the reaction engineering approach (REA) to drying processes is an ideal resource for researchers, academics and industry practitioners.

Starting with the formulation, modelling and applications of the lumped-REA, it goes on to detail the use of the REA to describe local evaporation and condensation, and its coupling with equations of conservation of heat and mass transfer, called the spatial-REA, to model non-equilibrium multiphase drying. Finally, it summarises other established drying models, discussing their features, limitations and comparisons with the REA.

Application examples featured throughout help fine-tune the models and implement them for process design, and the evaluation of existing drying processes and product quality during drying. Further uses of the principles of REA are demonstrated, including computational fluid dynamics-based modelling, and further expanded to model other simultaneous heat and mass transfer processes.

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‘The Reaction Engineering Approach (REA), which captures basic drying physics, is a simple yet effective mathematical model for practical applications of diverse drying processes. The intrinsic “fingerprint” of the drying phenomena can, in principle, be obtained through just one accurate drying experiment. The REA is easy to use with the guidance of featured application examples given in this book. This book is highly recommended for both academics and industry practitioners involved in any aspect of thermal drying.’

Zhanyong Li,
Tianjin University of Science and Technology,
China

‘An interesting book on a novel approach to mathematical modelling of an important process. Modelling Drying Processes: A Reaction Engineering Approach is the first attempt to summarize the REA to modelling in a single comprehensive reference source.’

Sakamon Devahastin,
King Mongkut’s University of Technology Thonburi,
Thailand
Modelling Drying Processes

A Reaction Engineering Approach

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Preface

Drying is one of the oldest and most effective methods for preserving food and biological materials. Low moisture content in foods prevents the growth of bacteria responsible for their deterioration so foods can have extended shelf-lives. When foods became abundant, trade became possible. Today, dried products are the main materials trading round the world but this is not limited to food products. Construction materials, textiles, electronic parts and appliances, biomass-based fuels, pharmaceutics and many other materials important to our daily lives and the business world are all included. Essentially over 80% of the products on Earth require drying as one of the steps in their production. Product quality and process parameters are interactive. Industrial drying is energy hungry; a process involving simultaneous heat, mass transfer and momentum transfer. Product quality is determined through compositional and structural rearrangements, as well as chemical reactions in some circumstances. For existing drying facilities, optimisation is often needed to achieve new goals such as energy reduction, quality improvements and development of new materials. There are also opportunities in designing dryer modifications or even brand new dryers that are superior in performance over conventional devices. Modelling of drying processes is very useful for these purposes.

A number of drying models have been proposed, which are conveniently classified into empirical and mechanistic models. The empirical models give advantages of being simple in their mathematical formulation. However, these models most often cannot explain the physics of drying and their application is limited since they are valid only for a particular set of drying conditions. On the other hand, the mechanistic models are derived based on fundamental phenomena that occur during drying. These phenomena are crucial in material science (and materials processing) though material scientists themselves may not have yet come to appreciate the process engineering aspects which impact on the product microstructure. Some of these models can capture the physics well. These models are, however, often mathematically complex and sometimes contain too many parameters, which need to be determined experimentally (prior to model predictions).

For some decades now, a comprehensive set of macroscopic equations has been developed and used to address heat and mass transfer and mechanical aspects related to drying. The application of macroscopic descriptions of drying (temperature, moisture and sometimes pressure) has been perfected over the past two decades, and relevance has been confirmed in many drying configurations. Some of these involve irreversible thermodynamics formulations, which are lengthy and have many model coefficients. These have
become the ‘classical’ approach. However, this classical approach has serious limitations. The concept of multi-scale and multi-physics addresses some of these limitations, e.g. coupled meso-scale and equipment scale problems. When a local thermodynamic equilibrium is not attained, however, the time scales usually overlap. This is a real multi-scale configuration and challenging in terms of the great demand in computational power and handling of mathematics. Several scales can be considered simultaneously, ranging from simple exchanges between macroscopic phases to comprehensive formulations in which time evolution of microscopic values and microscopic gradients is considered over a representative elementary volume, according to a recent review by Patrick Perre (for a review of modern computational and experimental tools relevant to the field of drying, see *Drying Technology*, 29, 1529–1541, 2011).

While exploring the detailed physics involved in drying using these multi-scale and multi-physics approaches, it is, from an engineering viewpoint, also important to develop new ideas establishing simpler models. In general, today industrial drying applications require mathematical models that are simple and easy to use. For practical purposes, an effective drying model should be simple, accurate, and able to capture the major physics of drying and its application should be robust. This model should also favour short computation time and it should be easy to establish parameters needed (experimentally) to help quicker decision-making in an industry environment (and with the lowest cost).

The reaction engineering approach (REA), which is a ‘middle path’ approach, perhaps between the empirical and the mechanistic models, was first thought about by the first author of this book, Chen, in 1996. Through much of the research on its possible applications, it has been revealed that the REA is indeed simple, accurate and robust enough to model many cases of drying, i.e., drying in a constant or variable environment. The REA has also been implemented in industry for prediction of spray dryer performance and shows good agreement with plant data for different scales in the dairy industry. It has also been extended to various other challenging systems of drying, such as polymer drying, intermittent drying, thermal-thick materials, infrared heating and microwave heating. The model is significantly easier to implement and requires less experimentation effort to establish the parameters needed, compared with the more fundamental models. The REA was first taken as a lumped model which does not need us to resolve the spatial distribution of water content, etc.; the lumped-REA (or L-REA), but in recent times, we have also extended the approach to describe spatially distributed systems; spatial-REA (or S-REA).

The REA approach has been initiated and exercised over the past 12 years and there is a significant amount of successful applications already illustrated. As mentioned earlier, it is a middle path between the rigorous theory that requires high-level mathematics and the empirical models that do not represent much physics. We can see, through our own practices and from other colleagues in the same area who have used the REA concept, it is a really straightforward approach to modelling some rather complex drying processes; hence, it is simple and cost-effective to establish accurate REA models to use in industry.

This book is the most fundamental and comprehensive description of the REA approach to drying modelling – the basic idea, rationale, mathematical description and implementation procedures – for various systems. This approach has been extended,
and experimented with, by several quality Ph.D. graduates, in particular, the second author, Aditya Putranto. Regarding the other more established theories, this book not only provides essential details so the readers can refer to them but also illustrates, by comparison, the physics involved in REA concepts. The disadvantages and advantages between theories are also briefly introduced. The book should benefit both academics in drying research and practicing engineers in industry. Undergraduate students in process engineering may also find it useful for quickly setting up a drying model for design purposes. The main emphasis of this book is how to apply the REA to reality. The book will also elaborate on potential applications of similar thinking to more complex reactive systems that couple with drying processes, hopefully to foster their future development.

Here, the modern ideas of microstructure development and product qualities created by drying processes, and in turn their impacts on moisture transfer, will be introduced. This should make the book more relevant in years to come.

_Xiao Dong Chen and Aditya Putranto_
Historical background

During my Ph.D. study in the Chemical and Process Engineering Department at Canterbury University, Christchurch, New Zealand, (1988–1990), the main task was to establish mechanistically the understanding of moisture influence on coal oxidation and the impact of moisture transfer in a packed coal particle bed on the development of spontaneous combustion. The experimental aspect was challenging both technically and physically. In addition to coal oxidation and its racemic measurement, I became very interested in the mechanisms of water evaporation and moisture transfer (liquid and vapour) in porous material. Dr Jim Stott (Reader of Chemical Engineering) was my main supervisor and Dr John Abrahamson (Senior Lecturer), in the same department, was my cosupervisor. Jim published some of the pioneering literature on the subject of spontaneous combustion of coal (1959) and built (largely by himself) ingenious experimental rigs. Dr Abrahamson was an inspirational and distinguished individual as well who has been credited as one of the first to have made a carbon nanotube (he called it the ‘carbon cylinder’) (1978), a theory of ball lightening (2000) and a theory of particle collision frequency in a turbulent field (1972). John was Jim’s student some years back.

Working with Jim on the subject of spontaneous combustion development in a moist coal bed has taught me that if the coal bed were completely saturated with water vapour under near ambient pressure (the institutional voids of the bed remain saturated with water vapour), the maximum temperature would remain at around 80°C. This was predicted from a numerical spontaneous combustion model involving mass transfer of moisture within the coal bed when assuming the vapour concentration in the bed is always saturated. Jim discovered this in the late 1960s, and later, in the 1970s, a Ph.D. student of his proved this more comprehensively. This aspect was more or less republished in 1990s by a research group in Europe (who were perhaps unaware of the work by Jim and his ex-students). However, if an equilibrium relationship between moisture content in the coal particles and vapour concentration in the air surrounding the particles can be adopted, a dry spot can be predicted and the maximum temperature will exceed the boiling temperature of water, therefore rising to an elevated temperature due to oxidation heat (Chen, 1992a). Of course, there are also other influences such as porosity, oxidation rate and oxygen transfer, heat transfer and, sometimes, fluid flow due to a pressure gradient. Nevertheless, this equilibrium relationship is what we are now so familiar with, termed the equilibrium isotherm in drying literature. The oxidation rate of coal itself was also found, in my own experiments, to vary with the residual water content (Chen and Stott, 1993) and I had gone to extra lengths to try to understand this