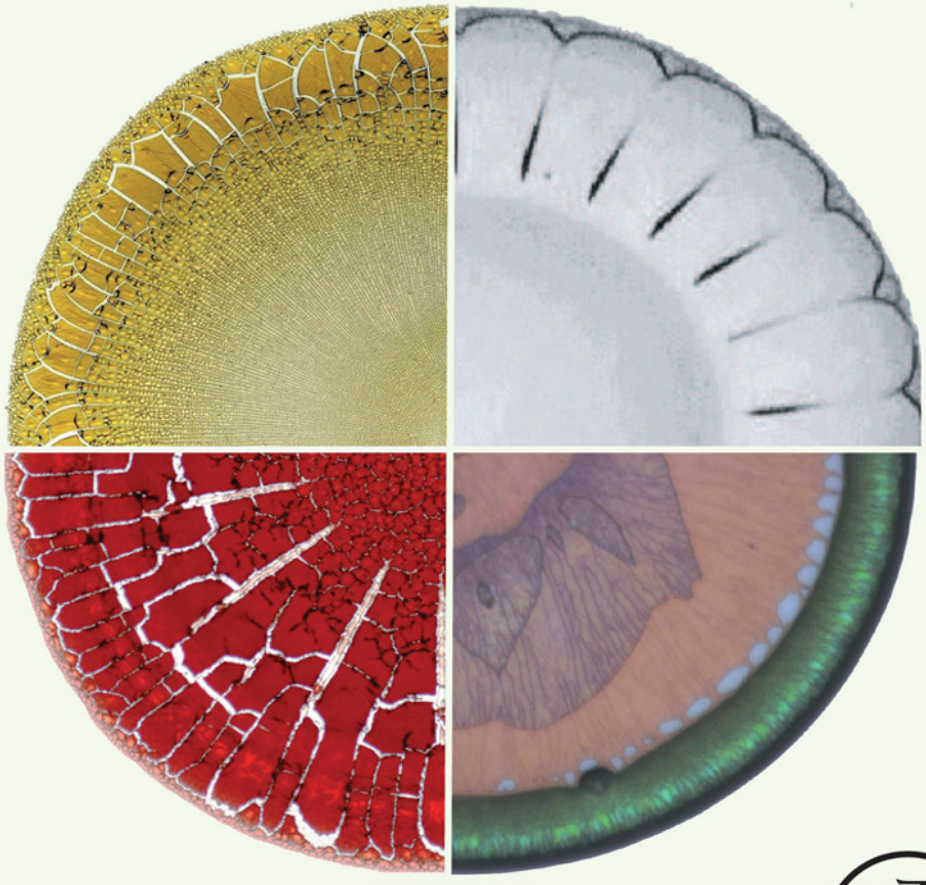
Droplet Wetting and Evaporation

From Pure to Complex Fluids

Edited by David Brutin



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Edited by

David Brutin

Aix-Marseille University
Marseille
France

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Preface

It is really a nice and fascinating book that is published here by David Brutin and some of his colleagues and friends, on "droplets considered as a small lab for wetting and evaporation." As David says, droplets spreading or evaporating on a substrate have of course motivated a huge number of studies, especially in the wetting field (de Gennes, 1985), where it is one of the cardinal case that one can imagine and realize, and also in diverse fields of coating (Kistler and Schweizer, 1997) and more generally engineering. However, it is only recently that the qualitative idea progressively emerges that a so small and fascinating object can become a very simple and nice lab inside which various secret laws of nature could be investigated simply and deeply under very well controled conditions.

The perhaps first sign of this evolution was, to my opinion, a series of remarkable papers from the Chicago group (Deegan, Nagel, Witten, and others) on the so-called "coffee stain" problem (Deegan et al., 1997). These authors realized that very surprising things were occuring in the vicinity of the contact line of a drying drop. Unsual conditions induced by the combined effect of evaporation and hydrodynamics led to an unexpected organization of the solute, and surprising self-organization patterns. This had a great impact and gave rise to a number of other ones on different aspects of this problem and of its generalizations. I was very lucky to be involved in this motion, during a rather short time, by co-organizing a small meeting in Leiden in 2010, with Tom Witen and Vincenzo Vittelli, in which I was surprised by the potentialities of this still exapanding subject, where three singularities were interacting at the same place (evaporation, hydrodynamics, and concentration). The complete understanding of this requires to master hydrodynamics, transferts, chemistry, soft matter, and evaporation, in a very interdisciplinary manner. This first branch of droplet studies was also progressively interacting with another emerging one: a growing number of works also adressed drop dynamics in condition of non-wetting, which led to surprising behaviors (superhydrophobic substrates, Leidenfrost levitation, drop impact and rolling, etc.). The accumulation of all these studies on droplets leads to another sign of this evolution, which was the multiplication of sessions "droplets" in several congresses (APS-DFD, Euromech, etc.), and that were federating an increasing number of research teams.

In some sense DROPLET 2013 was perhaps one of the first attempts to federate all these ones in a single motion, and arrived very timely. Very well organized by David and his collaborators, this meeting was really an oustanding success, in front of "Vieux Port de Marseille," which gives the occasion to many teams to exchange, discuss, federate themselves; and this book is a result among valuable ones of this great event. David has been able to identify and enroll famous collaborators with whom he had well coordinated, which gives this nice book. The great merit of the team is to have avoided to do some "Encyclopedia of Droplets" that would have been a never ending work... Instead, after giving to the reader some general principles on hydrodynamics, evaporation, and contact lines, the book focusses on several and fascinating hot topics, such as convection patterns in drops, self organization of drying induced fractures, drops on soft matter compounds, new repulsive substrates, investigations on biological compounds by drop drying, where, by the way, David realized remarkable and difficult things applicable to criminology (Brutin et al., 2011), and so on. It is rather a walk around the Droplet County that is proposed to the reader, and I wish to everyone to have the same pleasure as I had when discovering these new horizons.

I have no doubt that this book will be a very helpful tool for everyone wanting to learn in this new "Droplet field," and that it will catalyse new progresses in this expanding field. A great and nice book that I recommend to everyone!

Laurent Limat
Paris, April 12, 2015.

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Brutin, D., Sobac, B., Loquet, B., Sampol, J., 2011. Pattern formation in drying drops of blood. J. Fluid Mech. 667, 85–95.

Introduction

In the early 1800s, Thomas Young (1805) and Pierre-Simon Laplace (1806) conducted the first investigations on the wetting of droplets. They examined the wetting issues, the role of the contact angle, and the liquid/solid coupling nature driving the droplet problems. While a sessile droplet is a simple geometry, it is also a complex system to solve for real-life situations (metallic inks for inkjet printing, spreading of pesticides on leaves, drops of whole blood or blood serum spreading and drying for medical applications). By taking into account its wetting and its evaporation, this simple case becomes a very complex problem that has been studied by several teams worldwide. The complexity is mainly due to the physics involved, the full coupling with the substrate on which the drop sits (the Latin root of the word *sessile* means "on which one can sit"), the atmosphere, and the fluid nature (pure fluid, bi- or multiphases, or even containing colloids).

The idea for a book addressing the issues of sessile droplet wetting and evaporation came after the first workshop DROPLETS, organized in June 2013, at Aix-Marseille University, Marseille, France. Before the DROPLETS events, each team's work was presented in general conferences: the American Physical Society, Division of Fluid Dynamics (APS, DFD), or the European Colloids and Interface Society (ECIS). Before then, researchers working on droplets in the fields of chemical engineering, mechanical engineering, bioengineering, and surface science had no place to assemble. The workshop has successfully gathered more than 160 scientists, all of whom work in the field of sessile droplets and study the processes of wetting and evaporation. After the event, it was clear that a book on this topic was sorely needed for new scientists, masters and PhD students, and even established researchers who wanted to learn more. Thus, I asked some workshop participants to help me write this book, which covers most of the aspects of droplet wetting and evaporation.

Today, the topic of "droplet" and "evaporation" is the subject of more than 6700 papers published in the past 50 years (1964–2014) in referenced journals archived in the Scopus database. Because the total number of scientific publications also sharply increased in the same period for all areas of research in the life, health and physical sciences fields, the results were normalized and clearly show a linear increase in the percentage of works written by the scientific community. The number of publications dealing with "droplets" and "evaporation" has increased 10-fold in the last 50 years (Figure I.1).

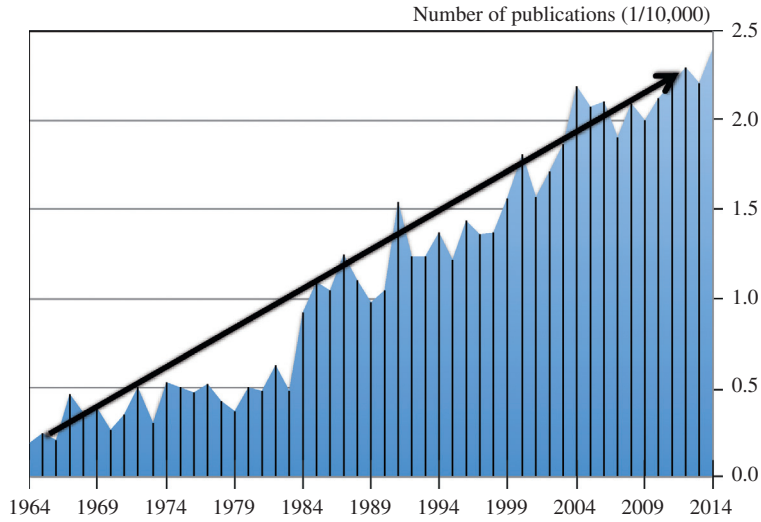

FIGURE I.1 Number of articles published between 1964 and 2014 having "droplet" and "evaporation" in their abstract, key words list, or title that are also referenced in the Scopus® database. The results are normalized by the total number of articles in the categories of "Life + Health + Physical" Sciences. *Scopus*®.

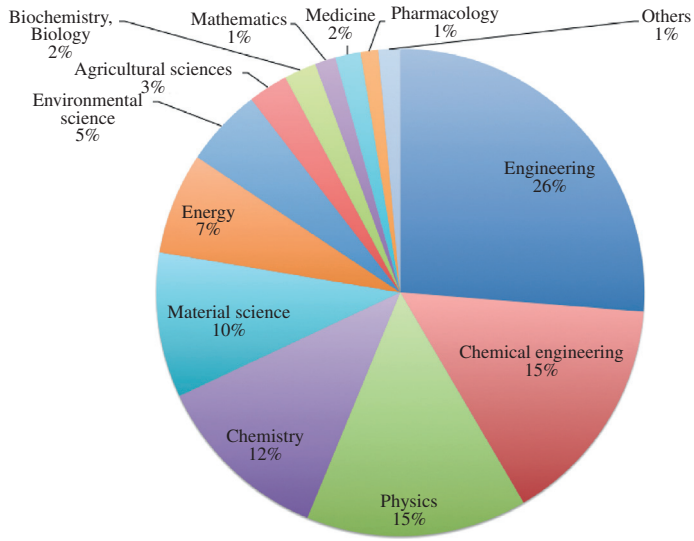

FIGURE I.2 Subject areas regarding the topics of "droplet" and "evaporation." *Scopus*®.

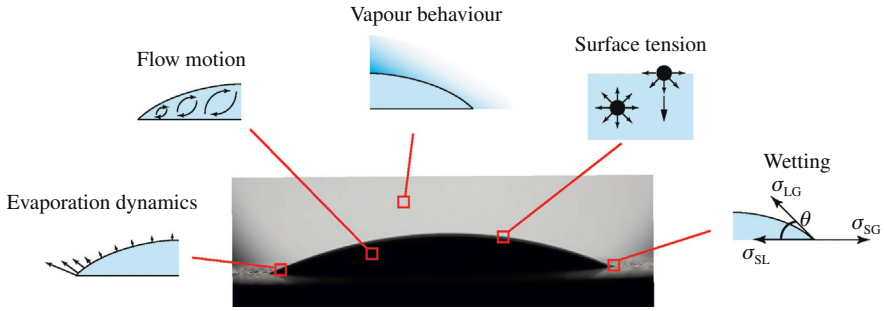

FIGURE I.3 Ways to address the topic of "Droplet Wetting and Evaporation."

Several domains are affected by this increase in publications. The distribution in 2014 shows a strong interest in engineering of more than 40%, fundamental physics and chemistry of 27%, material science of 10%, and energy of 7%. Energy is frequently discussed in published papers dealing with "droplet" and "evaporation," especially because of the applications (printing of complex fluids, spray cooling, DNA analysis) (Figure I.2).

This book contains five chapters that cover wetting and evaporation issues applied to sessile droplet configurations working with pure and complex fluids:

- Chapter 1 addresses wetting and spreading issues and provides the theoretical concepts.
- Chapter 2 addresses heat and mass transfer and presents the driving parameters.
- Chapter 3 addresses flow instabilities and details them either inside the droplet or in the vapor phase.
- Chapter 4 addresses drying complex fluids and soft matter applications and issues.
- Chapter 5 addresses the influence of external forces and presents unusual parameters.

Because the domain of sessile droplets is quite vast, it was not easy to structure the book, present the theoretical concepts, and analyze the work performed by the scientific community. A droplet can be viewed with the eyes of a chemist looking for wetting issues, colloid motions, and their influence on spreading and evaporation. The problem can also be addressed from a mechanical engineering point of view by looking at the internal flow motion or the vapor flow behavior around the evaporating droplet. There are several ways to address this topic, and they are summarized in Figure I.3. Almost all of them are covered in this book.

The mind map of the book is made of the book key words which can be found in the index. Each branch corresponds to a book chapter, but cross-links exist because the physics involved are strongly coupled (Figure I.4).

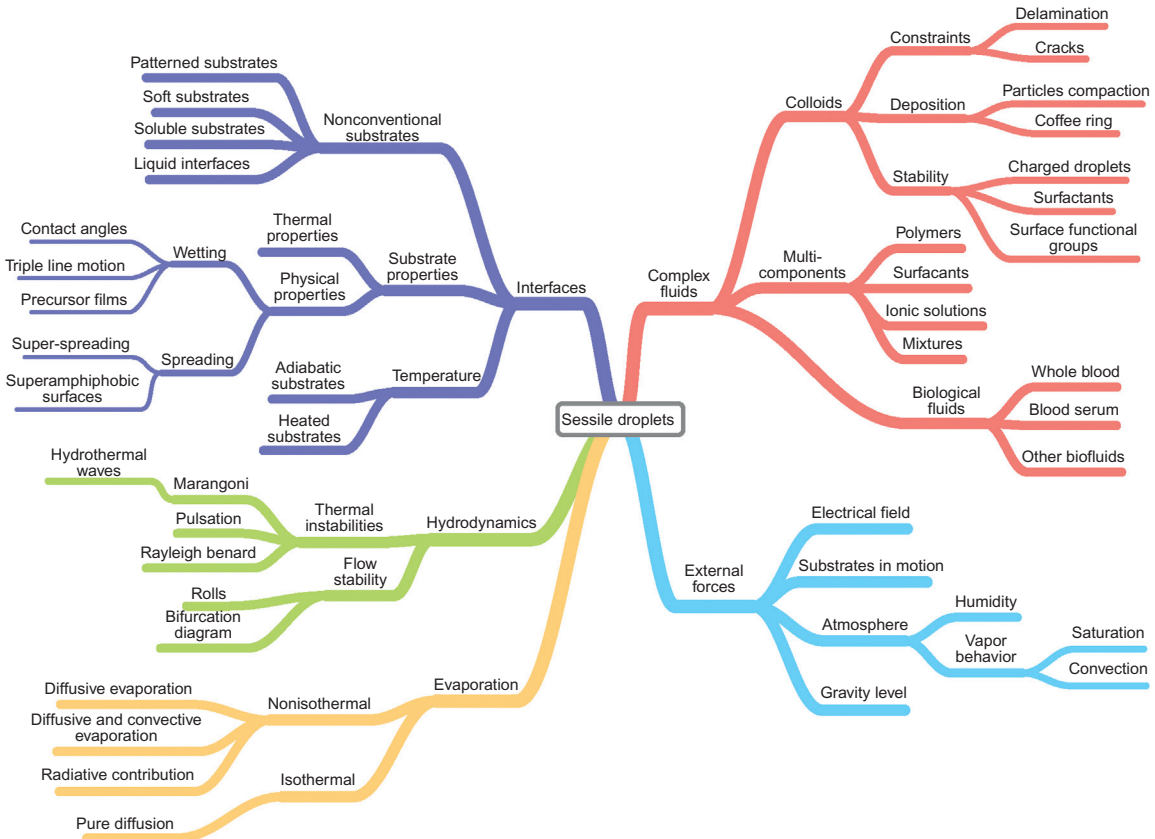

FIGURE I.4 Mind map and key words in the book.

The book is the result of several years of working on droplets as part of a stimulating community that is growing faster and faster all the time. It is the result of collaborative work. I owe much to my alumni who worked on studying droplets: Benjamin Sobac, Florian Carle and Wassim Bou-Zeid. I am also grateful to all other alumni who brought their bricks to this work. I extend my sincere thanks to Natasha Welford and Lisa M. Jones from the Elsevier team for their help and fruitful advices. I also thank all the members of the production team for their work. Finally, I owe much to my wife. Nathalie, you were a great support during this past year while I spent time on this book instead of you.

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Droplet Wetting and Evaporation

From Pure to Complex Fluids

Edited by David Brutin

The first comprehensive guide to the theory and applications of droplet wetting and evaporation, covering fundamental principles alongside interdisciplinary findings and developments

Key Features:

- Provides the broad, cross-subject coverage of theory and application needed for engineers, students and researchers to follow all major developments in this interdisciplinary field
- Begins with an accessible summary of fundamental theory before moving on to specific areas such as flow instabilities and the drying of complex fluid droplets
- Edited by the co-chair of the 1st International Workshop on Wetting and Evaporation: Droplets of Pure and Complex Fluids

Droplet Wetting and Evaporation: From Pure to Complex Fluids provides engineers, students and researchers with the first comprehensive guide to the theory and applications of droplet wetting and evaporation.

Beginning with an accessible summary of the relevant theoretical background, the book moves on to consider specific aspects such as coupled heat and mass transfer, all types of flow instabilities, and the drying of complex fluid droplets such as nanofluids or blood, with each chapter covering the principles of the subject alongside corresponding practical issues.

Covering a broad range of domains, from aerospace and materials to biomedical applications, ***Droplet Wetting and Evaporation*** brings together important results, challenges and approaches from the different communities leading the way in droplet research and development.

Droplet Wetting and Evaporation: From Pure to Complex Fluids is prefaced by Laurent Limat, Research Director at CNRS, MSC, Paris Diderot University. Laurent has extensive expertise on interfaces, wetting, non-linear physics, pattern and singularity formation and capillary phenomena in soft matter.

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Associate Professor Brutin is an emerging leader in the field of droplet research; he got his Ph.D in 2003 in Mechanical Engineering. With research and teaching experience in fluid mechanics, heat transfer and soft matter; he has an impressive record of publications on droplets and related topics in leading journals. In 2013 he co-organized the 1st International Workshop on Wetting and Evaporation: Droplets of Pure and Complex Fluids.

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