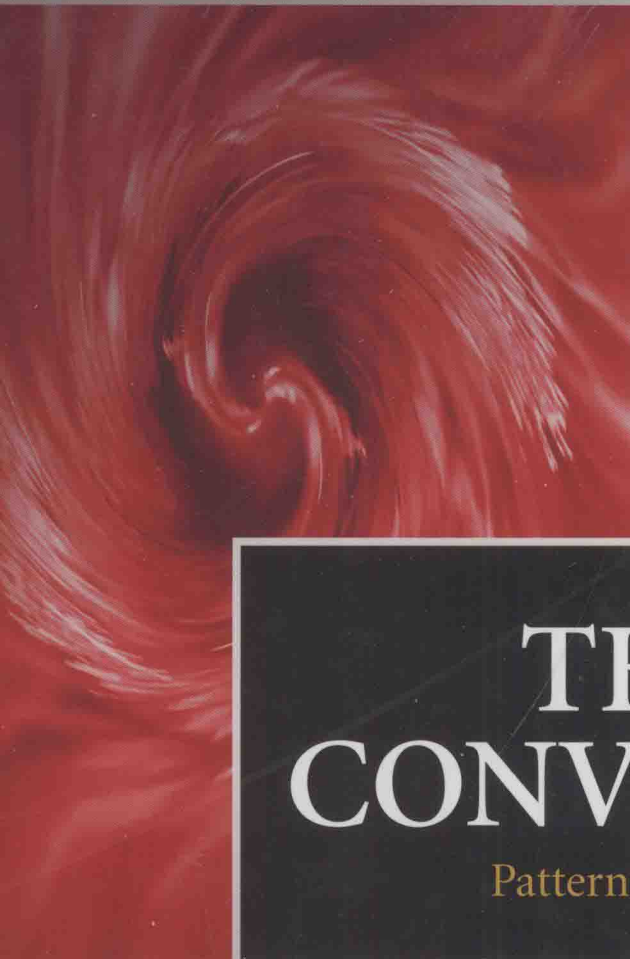
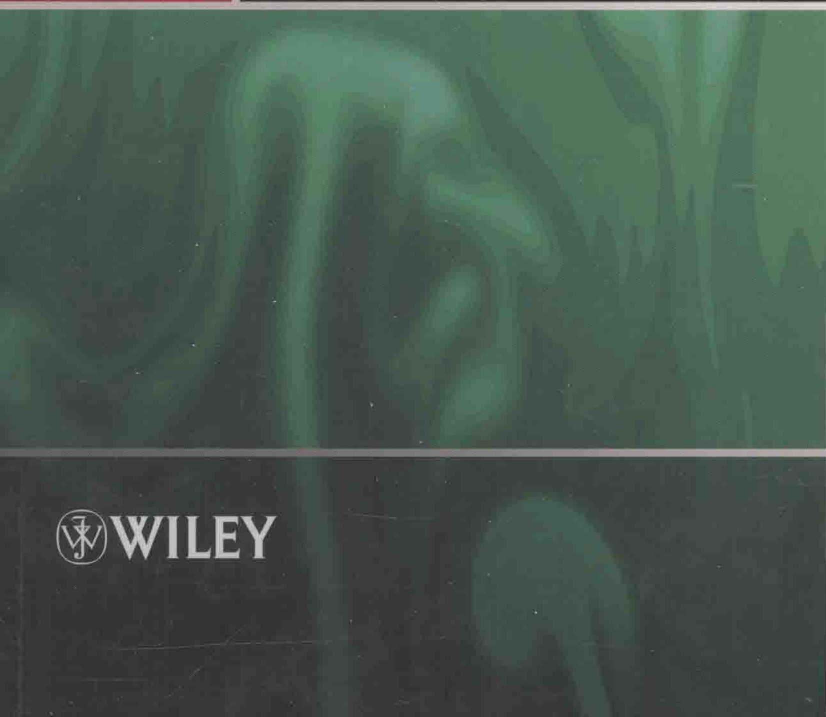
Marcello Lappa



THERMAL CONVECTION

Patterns, Evolution and Stability



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Thermal Convection: Patterns, Evolution and Stability

MARCELLO LAPPA
Naples, Italy

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Thermal Convection

To a red rose
. . . to my sons

Preface

Most of the fluid motion we are accustomed to on Earth is driven by gravity. The presence of Earth creates a gravitational field that acts to attract objects with a force that is inversely proportional to the square of the distance between the mass centre of the object and the centre of Earth. A very common example of gravity's impact on fluids is the creation of flows around our bodies, around the flame of a candle, in a container of water heated from below or from the side and in atmospheric and oceanic circulation at every scale.

The presence of flows of gravitational origin is not limited to fluids that affect our lives every day. They are also found inside planetary bodies. This is the reason why, for instance, continents 'move' (the 'solid' Earth itself undergoes a fluid-like internal circulation on time-scales of millions of years, the surface expression of which is continental drift) and a magnetic field is present around our planet (as a consequence of liquid metal motion in the Earth 'core').

Gravitational attraction is a fundamental property of matter that exists throughout the known universe; hence fluid motion of a gravitational origin also occurs in and around other celestial bodies and is presumed to play an important role in the dynamics of stars like the Sun.

Instability of such flows and their transition to turbulence are widespread phenomena in the natural environment at several scales and are at the root of typical problems in meteorology, oceanography, geophysics and astrophysics.

The possible origin of natural flows, however, is not limited to the action of the gravitational force. Other volume or 'surface' forces may be involved in the process related to the generation of fluid motion and ensuing evolutionary progress.

In particular, in the presence of a free interface (e.g. a surface separating two immiscible liquids or a liquid and a gas), surface tension-driven convection (also referred to as 'Marangoni' flow) may arise as a consequence of temperature or concentration gradients.

In such a context, it should be stressed that the universal nature of all these fluid phenomena makes their study fundamental not only to science, but also to engineering and industrial practical applications (e.g. the processing of metal alloys and inorganic or organic emulsions, cooling systems, the production of semiconductor crystals and various biological and biotechnological processes). The study of these topics has extensive background application in many fields.

As a relevant and important example, most widely used technologies for single-crystalline materials (e.g. horizontal and vertical Bridgman growth, Czochralski method, floating-zone technique) are affected by the presence of fluid convection. All conventional melt growth configurations require, in fact, the application of thermal gradients across the phase boundary: the axial and/or radial components of these gradients are destabilizing and provide driving forces for free convection in all fluid phases involved. Melt growth processes are, therefore, subject to varying heat- and mass-transfer conditions, which in recent years have been found to be directly or indirectly responsible for most bulk deficiencies in many materials. In particular, instabilities of the melt flow usually lead to three-dimensional oscillatory effects which strongly affect the quality of the growing crystals at microscopic scale length and therefore are very undesirable.

Some of these effects are known to be independent of gravity, that is, they are related to the other types of forces mentioned before.

Along these lines, it is worth mentioning that (because in many circumstances the influence of gravity on fluids is strong and masks or overshadows these important factors), a number of experiments have been carried out in recent years on orbiting platforms (the so-called 'microgravity' conditions). The peculiar behaviour of physical systems in space, and ultimately the interest in this 'new' environment, have come from the virtual disappearance of the gravity forces and related effects mentioned above and the appearance of phenomena unobservable on Earth, especially those driven by surface forces (that become largely predominant when terrestrial gravity is removed). The use of such an environment has also led, however, to the identification of a new type of fluid motion induced by the presence of 'vibrations' of the considered orbiting platform (usually referred to as g-jitters). This kind of convection, initially studied due to its perturbing and undesired influence on microgravity experiments, has recently witnessed renewed interest due to its possible application in terrestrial conditions as a means to 'control' flow intensity and patterning in other types of convection (as a possible variant to the use of magnetic fields traditionally employed for such a purpose).

Aims and Scope

As a natural consequence of all the arguments illustrated above, the present book is devoted to a critical, focused and 'comparative' study of all these different types of thermal convection.

Gravitational (also referred to in the literature as 'natural' or buoyancy), surface tension-driven, vibrational and magnetic flows are considered in various geometric models (infinite horizontal and vertical layers, open and closed geometries, shallow and tall cavities, cubic and parallelepiped slots, annular and spherical configurations, cylindrical enclosures, floating zones, liquid bridges, etc., many of which have enjoyed widespread use over recent years as 'paradigm' models for the study of these topics), under various heating conditions (from below, from above or from the side), for different fluids (liquid metals, molten salts and semiconductors, gases, water, oils, many organic and inorganic transparent liquids, etc.) and possible combinations of all these variants.

A significant effort is provided to illustrate the genesis of these kinds of flows, the governing nondimensional parameters, the scaling properties, their structure and, in particular, the stability behaviour and the possible bifurcations to different patterns of symmetry and/or spatiotemporal regimes. The book presents, in fact, a discussion of the main modes of two- and three-dimensional flows, pattern defects and the scenarios of convection-regime changes (together with the related transitional stages of evolution). To name some examples: striped patterns, various types of planforms (related to Rayleigh–Bénard or Marangoni–Bénard convection), textures (hexagons, squares, triangles, diamonds, spirals, panam structures, targets, spoke pattern), rhombic, square and star-like 'lattices' or 'super-lattices' (in vibrational convection), multiplume and multicellular configurations, cats-eye structures, patterns exhibiting the shape of a 'flower', a variety of symmetry-breaking effects, and so on.

A categorization and description of many kinds (both canonical and 'exotic') of instability are provided; to name just a few: Eckhaus, oscillatory skewed varicose, cross-roll, bimodal, the Busse oscillatory instability, zig-zag, knot, oscillatory blob, spiral-defect chaos, transverse hydrodynamic modes, oscillatory longitudinal rolls, transverse, longitudinal and oblique hydrothermal waves, steady and oscillatory multicellular flows, pulsating and rotating regimes, and so on, with the related discussion not limited to the first bifurcation of the flow, but also considering secondary, tertiary and high-order states.

Some emphasis is also given to the transition to chaos, related theories and possible means of flow control.

The analysis, moreover, does not cover only the cases in which all these types of convection (thermogravitational, thermocapillary, thermovibrational) act separately. Significant space is also devoted to elucidate the possible 'interplay' of several effects in situations where driving forces of different nature are simultaneously responsible for the generation of fluid motion. This subject (hybrid or mixed convection) is of particular importance as the identification of the most dominant mechanism and/or the mutual interference of different mechanisms involved with a comparable intensity may help researchers in elaborating rational guidelines relating to physical factors that can increase the probability of success in practical technological processes.

A number of existing analyses are reviewed and discussed through a focused and critical comparison of experimental and numerical results and theoretical arguments introduced over the years by investigators to explain the observed phenomena. The text has elicited information from about 100 of the author's relevant and recent papers and about 1000 analyses available in the literature to illustrate possible approaches to the considered problems, practical applications and the ensuing insights into the physics.

A deductive approach is followed with systems of growing complexity being treated as the discussion progresses.

The book, however, is not limited to a systematic survey of landmark and recent results in the literature.

Specific experimental and numerical examples are conceived and presented to provide inputs for an increased understanding of the underlying fluid flow mechanisms. Of course, an important part of these examples is based on numerical simulations (CFD). This branch of fluid dynamics complements experimental and theoretical fluid dynamics by providing an alternative cost-effective means of simulating real processes. It offers the means of testing theoretical advances for conditions often unavailable experimentally or having a prohibitive cost.

To summarize, the book progresses with the aid and support of both experimental results and numerical simulations for a better representation of the structure of convection and moves through very focused examples and situations, many of which are of a prototypical nature (some unpublished and heretofore unseen material is used to support the discussions).

The declared objectives are:

(a) to provide the reader with an ensemble picture of the subject (illustrating the state-of-the-art and providing researchers from universities and industry with a basis on which they are able to estimate the possible impact of a variety of parameters);
(b) to clarify some still unresolved controversies pertaining to the physical nature of the dominant driving force responsible for asymmetric/oscillatory convection in various natural phenomena and/or technologically important processes;
(c) to elucidate some unexpected theoretical kinships existing among fluid-mechanical behaviours arising in different contexts (such a philosophy, in particular, being used in the attempt to build a common theoretical source for the community of fluid physicists under the optimistic idea that an ongoing, mutually beneficial dialogue is established among different branches of research in these fields).

Each chapter of the book deals with a different aspect of the aforementioned topics, providing the necessary background information (i.e. literature, fundamental concepts, equations and mathematical models, information on the experimental and numerical techniques, etc.), focusing on the latest advances, describing in detail the insights into the physics provided by the experiments and/or numerical simulations and introducing (where necessary) theoretical and critical links with the other book chapters and related topics.

As anticipated, the final goal of such a treatise is to help the scientific community significantly in elaborating and validating new, more complex models, in accelerating the current trend towards predictable and reproducible natural phenomena and finally in establishing an adequate scientific foundation to industrial processes which are still conducted on a largely empirical basis.

In practice, the text is conceived in order to be a useful reference guide for other specialists in these disciplines (including professionals in the metallurgy and foundry field; researchers and scientists who are now coordinating their efforts to improve the quality of semiconductor or macromolecular crystals; organic chemists and materials scientists; and atmosphere and planetary physicists) and also an advanced-level text for students taking part in courses on the physics of fluids, fluid mechanics, the behaviour and evolution of nonlinear systems, environmental phenomena and materials engineering. It is directed at readers already engaged or starting to be engaged in these topics. Physicists, engineers, designers and students will find the necessary information and revealing insights into the behaviour of many phenomena (including, as outlined before, both historical developments and very recent contributions).

Finally, it is also worth pointing out that the study of pattern formation (convective flows can form more or less ordered spatial structures) also falls under the broader heading of nonequilibrium phenomena. Beyond practical applications, it is therefore clear that these problems also exert an appeal to researchers and scientists as a consequence of the complexity of the possible stages of evolution, of the nonlinear behaviour and because these organized structures are aesthetically and philosophically pleasing as well as irresistible to theoretical physicists.

This complexity is shared with other systems in Nature and constitutes a remarkable challenge for any theoretical model. Indeed, convection problems are a rich source of material propaedeutical to the development of new ideas concerning the relationship between order and chaos in fluid dynamics and, in general, between simplicity and complexity in the structure and behaviour of systems governed by nonlinear equations.

In view of the foregoing discussion, there is no doubt that elucidating the mechanisms for the formation and evolution of hydrodynamic structures can be regarded as a subject of paramount importance not only for the aforementioned meteorology, oceanography, astrophysics, geophysics and (on a smaller scale) crystal growth, the processing of metal alloys and a variety of other technological processes, but also from an 'ideological' synergetic point of view for further progress in the understanding of pattern-forming systems of different nature.

Unlike earlier books on the subject, here, even if partial differential equations and related methods of solution are widely used in the text and CFD is actually at the root of many of the proposed examples, the heavy mathematical background underlying and governing the behaviours illustrated is kept to the minimum. Much of the available space is devoted to the description (both qualitative and quantitative) of the spatial and temporal convection structures, related thresholds in terms of characteristic numbers and to the 'physics'. This is done under the optimistic hope that such a philosophy may significantly increase the readability of the book and, in particular, make it understandable also to those individuals who are not 'pure' fluid physicists or mathematicians.

In the same spirit, the use of jargon is limited as much as possible and most of the mathematical arguments are concentrated in the first chapter (this chapter is devoted to the description of the numerical algorithms used to perform the time integration, to compute directly the steady or oscillatory states and to investigate their stability), allowing readers who are not interested in these aspects to skip them and jump directly into the results.

Marcello Lappa

Acknowledgements

This book is a composite of many ideas. It was authored between 2006 and 2009 in the pleasant atmosphere provided by my writing desk and warm lamp at home, especially in the evening and at night.

It was originally conceived (in 2005) as an enriched version of Chapter 2 of my earlier monograph *Fluids, Materials and Microgravity*, published in 2004 by Elsevier Science, for which I was preparing a second edition. After writing about 100 pages, I realized, however, that the subject of thermal convection would deserve its own separate and exhaustive treatment.

I gratefully acknowledge the many unknown reviewers selected by John Wiley & Sons, who initially examined the new book project, for their critical reading and valuable comments on the work.

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Finally, I would like to mention that a significant amount of the insights that I have tried to convey in this book resulted from the last 5 years of work I have done in the position of Editor-in-Chief of the journal *Fluid Dynamics and Materials Processing* (FDMP), which obliged me to keep myself informed on the latest advancements in the field, to interact almost daily with article authors, reviewers, experts in various fields and other Editorial Board members, to whom collectively I also express my appreciation.

As a concluding remark, let me also point out that the overt intention of including so many references (there are more than 1000) is to encourage readers and students to follow up on various details and, most importantly, not to limit their readings to the relatively synthetic and didactic account I have provided here. It is obvious that if one tries to survey the developments of the last 200 years, one cannot follow carefully all the twigs of the tree. It is also evident that one will possibly emphasize some results due to personal taste, interests and experiences. Let me apologize for this right at the beginning.

To contact the author:
Marcello Lappa
Via Salvator Rosa 53
San Giorgio a Cremano (Na)
80046 – Italy
Email: marlappa@unina.it
lappa@thermalconvection.net
fdmp@techscience.com
Websites: www.thermalconvection.net
www.fluidsandmaterials.com
www.techscience.com/FDMP

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