

Preface

In 2013 I had the unique opportunity of being an invited keynote speaker at the ASME Summer Heat Transfer Conference, held from July 14–19 in Minneapolis, Minnesota, which marked the 75th Anniversary of the founding of the Heat Transfer Division of ASME. Prof. S.A. Sherif from the University of Florida at Gainesville, who was the General Conference Chair and a long time friend, kindly introduced me to Prof. Francis A. Kulacki from the University of Minnesota, Chair of the 75th Anniversary Steering Committee, whom I knew from his many publications and achievements, but never had the chance to meet until then. Prof. Kulacki gave me the honor of attending the lecture, demonstrating his vivid interest and motivation on analytical heat and mass transfer, and afterwards brought to me the very kind invitation for contributing with a publication on integral transforms in heat and mass transfer, based on that lecture, to the Springer Brief Series under his coordination.

The lecture title was “75 Years of Integral Transforms in Heat and Mass Transfer: From an Analytical to a Hybrid Numerical-Analytical-Experimental Approach”, aimed at reviewing the last 75 years on integral transforms in heat and mass transfer, with special emphasis on showing its extension to various classes of *a priori* non-transformable problems, as the flexible hybrid numerical-analytical version of the integral transform method, well known as the Generalized Integral Transform Technique (GITT) (Cotta 1990, 1993, 1994a, b). However, at the same conference, a second paper from our group was presented (Knupp et al. 2013), with the title “Conjugated Heat Transfer in Heat Spreaders with Micro-Channels” that also dealt with the application of the Generalized Integral Transform Technique (GITT), combined with a single domain reformulation strategy, to analyze conjugated heat transfer within a complex configuration formed of multiple micro-channels within a polymeric substrate. The interest raised by this second work was beyond our expectations, attracting both audiences on computational methods and on micro-scale heat transfer. Therefore, the concept of the present book, with focus on integral transforms application in heat and fluid flow analysis of microchannels and microsystems, was then proposed to Prof. Kulacki. The proposal was written down by the end of October 2013, and the first versions of the Chapters were

assembled by May 2014, before they were tested in a graduate level course as supplementary material, during the second semester of 2014. At that time I had already invited Prof. Carolina Naveira-Cotta, my wife and collaborator, and Prof. Diego C. Knupp, the first graduated DSc jointly advised by myself and Carolina, also a close collaborator, to contribute on this project as my co-authors. I could not be more fortunate in these invitations, since both became very enthusiastic about the project and were very helpful in all the stages of the book preparation. Prof. Naveira-Cotta heads the Nano and Microfluidics and Microsystems Lab at COPPE, Federal University of Rio de Janeiro, and Prof. Knupp works in the Heat and Mass Transfer Lab at the State University of Rio de Janeiro, UERJ, Nova Friburgo, both in Brazil. In lack of a more logical criterion, we have decided to list our names in the cover page following the alphabetical order of our citation names.

The interest on micro-scale heat transfer within our group at COPPE/UFRJ started back in 1997 (Mikhailov and Cotta 1997), after Prof. Mikhail D. Mikhailov from Sofia, Bulgaria, moved to work with us in Rio de Janeiro, at that specific occasion mainly motivated by contributing to the work of (Barron et al. 1996), improving their analytical solution through a more robust computation of the associated eigenvalues employing the *Mathematica* system. The interest raised by this initial effort was markedly increased along the years by the close interactions with Prof. Sadik Kakaç, University of Miami, USA, and later on TOBB University, Ankara, Turkey, Prof. Dimos Poulikakos, ETH, Zurich, Prof. Patrick Tabeling, ESPCI, Paris, Profs. Jacques Padet, Mohammed Lachi and Mourad Rebay, Université de Reims, Prof. Yildiz Bayazitoglu, Rice University, Houston, Prof. Olivier Fudym, École des Mines, Albi, Prof. Manish Tiwari, ETH/Zurich, presently at UCL, London, UK, Profs. Jean Christophe Batsale and Christophe Pradère, from ENSAM/Bordeaux, France, Prof. Luiz Otávio Saraiva Ferreira, UNICAMP, Brazil, and Prof. John Rose, Queen's Mary College, London. The first two MSc thesis were then concluded in 2003/2004 (Castilho 2003; Castellões 2004), the first one advised by Profs. Rodrigo Guedes and Francesco Scofano, at the Military Institute of Engineering, in Rio de Janeiro, and the first sponsored research project was initiated in 2004 (CNPq, Brazil). The participation as invited lecturer in the NATO Advanced Studies Institutes in 2004 (Cotta et al. 2004a, b) and 2009 (Cotta et al. 2009a, b), organized and coordinated by Prof. Sadik Kakaç, was crucial for the exchange of ideas with worldwide leaders in this area and for the maturity of this line of research within our group. Then, parallel to the advancement of the theoretical research on heat and fluid flow in microsystems, aimed at progressively exploring more complex modeling at the micro-scale, an experimental infrastructure was established, based on non-intrusive measurement techniques, such as infrared thermography with microscopic lens and micro-PIV/micro-LIF, so as to allow for a complete and critical effort on the comparison of theoretical and experimental results for different microsystems and physical situations. In addition, along the last few years, the theoretical approach has been further developed and employed in close collaboration with our co-worker and closest collaborator, Prof. Helcio R.B. Orlando, of COPPE/UFRJ, Brazil, towards the solution of computationally intensive inverse problem analysis, in combination with Bayesian Inference and non-intrusive experimental techniques, when the analytic

nature of the method brings up the possibility of working on the integral transformed experimental domain, with marked reduction on computation effort through data collapsing (Naveira-Cotta et al. 2011; Knupp et al. 2012). Such initiatives have then induced the creation, in 2011, of the Nano and Microfluidics and Microsystems Lab (LabMEMS), at COPPE/UFRJ, which now concentrates the essential infrastructure for design, fabrication, characterization, and testing of microsystems in different platforms and for various applications. This laboratory is part of the infrastructure complex offered by the establishment of the Interdisciplinary Nucleus of Fluid Dynamics (NIDF) also recently created at COPPE/UFRJ.

This book is then built on top of this background, being an attempt of consolidating part of this line of research into a single volume of the Mechanical Engineering Series. The first chapter brings an introduction and motivation to the analysis of heat and fluid flow in microchannels and microsystems, and the important aspects to be considered when modeling at this microscale. It also presents a brief review and a melt pot of new ideas on the GITT approach, discussing different aspects of interest to the micro-scale heat and fluid flow analysis, reviewed in recent invited lectures (Cotta et al. 2012, 2013, 2014a, b), besides the unpublished one presented at the ASME Minnesota heat transfer conference in 2013. The second chapter is devoted to the integral transform analysis of heat and fluid flow in single microchannels. It is arranged in a sequence of increasing complexity, dealing with transient and periodic states, slip flow, viscous dissipation, axial diffusion effects, electrosmotic flow, inverse problem analysis, rough and corrugated walls, conjugated problems, and channels with irregular cross sections. The third chapter has a focus on actually built microsystems, with multichannel configurations that have also been experimentally analyzed. The analysis deals with comparing the obtained GITT solutions with those from the experimental runs, and also against numerical results from commercial CFD codes. In light of the markedly different length and time scales present in actual microsystems simulations, it is expected that the computational effort on the implementation of purely discrete approaches can be particularly critical. Therefore, the hybrid numerical–analytical nature of the present methodology provides an interesting alternative to the fully numerical approaches.

This Preface would not be complete without giving credit to the students and ex-students, now our colleagues, whose articles and theses are part of a coherent and collaborative development of this research line. A special word is dedicated to Ms. Patricia Oliva Soares, whose MSc dissertation is summarized in section 2.3, and who left us very early and very young, before having the chance to fulfil her dreams. I wish to particularly express my gratitude to Prof. Luiz Bevilacqua, Prof. Átila Silva Freire, and Prof. Fernando Duda, who have closely supported the creation and establishment of this research area and its laboratory at COPPE/UFRJ. Finally, we are thankful and dedicate this effort to our families, for once more accepting our partial absence in critical moments for completion of this mission.

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