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The world is a dangerous place, not because of those who do evil, but because of those who look on and do nothing.

Albert Einstein

To Violeta,
for showing grandpa the real meaning of life

Preface

During my academic career at Instituto Tecnológico de Aeronáutica (ITA), Brazil, back in the late 1990s, we started working on the topic of turbulent flows in porous media. I had the pleasure to work with several outstanding students in that topic, graduating a number of doctoral and master's students and ending up with the publication of a book on *Turbulence in Porous Media—Modeling and Application* (ISBN 978-0-080-98241-0), by Elsevier, and two other books with Springer, in this very Springer Briefs in Applied Sciences and Technology series in Computational Mechanics, which were entitled *Thermal Non-Equilibrium in Heterogeneous Media* (ISBN 978-3-319-14665-2) and *Turbulent Impinging Jets into Porous Materials* (ISBN 978-3-642-28275-1), respectively. We called that long-term research endeavor the "First Wave" of development of our group.

A few years back, in early 2018, we were approached by a prominent oil and gas company in the country with a problem of sealing depleted oil wells via a thermal source. The number of wells to be depleted in the next 20 years, in Brazil and worldwide, when compared to the overwhelming cost to plug and abandon all wellbores in line with the current energy transition process, was preoccupying. We then start digging into this realm and called this next challenge our "Second Wave" of development. A new breed of students got involved, and this has led to the graduation of three more doctors and eight new master's students, in a time span of just five years. Unfortunately, companies and academia have usually distinct time scales, and our long-term funding was cut short in early 2022. Groundbreaking technologies need time to be developed and get mature in order to safely reach the market, which cannot be done "overnight" as regrettably expected by some. Nevertheless, we moved on with the help of federal and state agencies, as below, and present in this booklet a compilation of our recent work.

As in the earlier two issues with Springer Briefs, I am deeply thankful to Prof. Dr.-Ing. Andreas Öchsner, Editor-in-Chief of the Springer book series on *Advanced Structured Materials*, and Dr. Christoph Baumann, Springer Senior Engineering Editor.

Once more the continuous support from our research funding agencies in Brazil, namely CNPq, CAPES and FAPESP, is greatly appreciated. We also acknowledge the

initial support of PETROBRAS, Brazil. In this volume, most of the presented material is related to graduate research work done by my former students, in particular those conducted by Dr. Kesiany M. de Souza, Dr. Gabriel S. de Andrade and Dr. Fabrício J. C. Pena, as well as master's graduates Anatole J. U. Hodierne, Igor A. de Carvalho, Santiago H. P. Maciel, Andre S. Souza and Ernandes J. G. do Nascimento. Thanks are also due to our post-doc researchers Dr. Roberta R. Ribeiro and Dr. Fernando A. Rodrigues. To them and to all my other former students and collaborators who have contributed to our efforts over the last twenty-five years, helping us to surf over our "First and Second Waves" of development, my sincere thanks.

São José dos Campos, Brazil Marcelo J. S. de Lemos
December 2023

Overview

Everything that has a start must have an end. This is also the case of oil and gas wells that, for more than a century, have been drilled elsewhere. Nowadays, due to stringent environmental regulations, no-longer profitable oil wells must adhere to technical norms where conditions are set in a way to guarantee that no leaks will occur after a plug and abandonment operation (P&A). In addition, the environmental liability posed by thousands of wells in operation to date, associated with the ever-greater cost of P&A operations, has driven research groups and oil and gas companies worldwide to search for more reliable and cost-effective technologies, promoting a race to overcome the inevitable "P&A wave" that is fast approaching in the next two decades.

One of such technologies deals with placing a heat emitter in the borehole, setting up a highly exothermic reaction that melts the productions tube, casing, cement, and surrounding rock, forming a solid plug at the sealing location after the cooldown of the molten material. In principle, the time and cost required for the entire sealing operation, when compared to more traditional P&A techniques such as cementation, are expected to be a fraction of current technologies used worldwide.

Motivated by the above, this book will then review a systematic study done with the aim of understanding and modeling of the complex Multiphysics involved during thermite reaction and melting of oil well components. This research work involved the development of analytical, numerical and experimental tools that are expected to shed some light on the development of game-changing thermal technologies for P&A, ultimately contributing the energy transition process from a carbon-based to a carbon-free economy.