Preface

While there is much debate as to the extent of fossil fuel reserves, increasing consumption is driving a long term rise in fuel prices. Leaving climate and environmental concerns to one side, more efficient sources of energy will be needed in the near future. Meanwhile, although technology is forever marching on, to all intents and purposes power plants in their traditional form hit their efficiency limits a few decades ago.

There are now two ways to increase the efficiency of energy conversion from the chemical state into the much-required electricity. They are: to use binary or even tertiary systems (e.g. gas turbine + steam turbine + Organic Rankine Cycle), or to use non-heat cycle based engines—thereby working around the Carnot limitation.

Fuel cells produce electricity directly from fuel through electrochemical processes, and hence bypass Carnot engine efficiency constraints. This could deliver unparalleled levels of efficiency in electricity generation. The downside is that the chemical reactions in themselves are a source of irreversibility, which mitigates fuel cell efficiency to some extent.

The range of application for fuel cell technology is immense, including microcapacity units, personal devices, transport, power supply units in buildings and other locations, e.g. distributed generation and power plants. This great potential is crying out to be tapped.

High temperature oxide fuel cells (SOFCs) are the most efficient devices for the conversion of chemical energy from hydrocarbon fuels into electricity. Recent years have witnessed an upsurge of interest in them for use in clean distributed generation systems. A stark demonstration of the technical feasibility and reliability of tubular SOFCs came through the very successful, 2-year long operation of a co-generation power plant with installed capacity of 100 kW without a performance penalty.

Currently, the main thrust of research work is going into cutting fuel cell manufacturing costs so as to increase competitiveness vis-à-vis other energy technologies. Numerous alternative design solutions have been proposed and many national and international research programs have played active roles. Prominent among them are: Solid State Energy Conversion Alliance (SECA) and National Energy Technology Laboratory [1] in the USA, EU Framework Programmes (6th and 7th) and the New Energy and Industrial Technology Development Organization (NEDO) in Japan. Expenditure on fuel cell research appears locked in on an upward trend for the foreseeable future.

In addition to reducing initial costs, research programs emphasize possible application in housing, transport and military environments—mainly due to the high degree of flexibility of the type of fuel cell involved. Since gasoline and diesel fueled cells could act as an auxiliary source of electrical power, these cells might even find a place in the automotive industry.

To place current trends in some broader historical perspective, we as engineers, researchers and scientists have spent years huddled together modeling and simulating classical power plants to achieve ever higher efficiencies in energy conversion. The most advanced solution we came up with in the early years was using hydrogen to fuel a steam turbine based cycle and burn it with oxygen in the steam flow. The range of temperatures used reached values of 1700°C. For these ultra-high parameters, forecast efficiency was 60%. Next, we turned our attention to avoid using heat engines entirely, and by doing so ducked under the Carnot hurdle. The obvious choice was fuel cells: at first glance seemingly ideal devices, but suffering from their own limitations mainly due to their electrochemical nature. The end result was disappointing: relatively low levels of efficiencies (up to 40%). Moving on, the combination of fuel cell with a classical power system looked to offer a promising path ahead, pooling the plus points of fuel cells and heat cycles.

We hit a dead-end. It was brutal. The fuel cell models proved utterly useless for power plant modeling—mainly because too much effort had to be devoted to the intricacies of the arcane little electrochemical processes which occur on cell surfaces. We could not distinguish between the “design point” model and “off-design” operation of the object. There was little correlation between the amount of fuel delivered and the cell voltage, etc. The models developed at that time were overly sensitive to minute changes in parameters and that threw a proverbial spanner into the process of optimizing the systems.

And so we started on developing our own fuel cell models for power plant modeling purposes. To do this, we had to go back to first principles of solid oxide fuel cells and forge relationships compatible with other models of component parts of the system such as turbines, compressors, heat exchangers etc. nuts and bolts.

With the best will in the world, even an inspirational model is worth little without reliable validation. Hard experimental data are needed. Numerous papers came to hand in which experimental investigations were performed and results presented. Those results contained mainly fuel cell characteristics based on the current–voltage curve alone. A lack of narrative about experimental procedure and poor information on flow parameters during experiments would seriously undermine any attempt at a validation process for the models. It was crucial to obtain sound experimental data together with a complete rundown on the experimental procedures used. Almost out of the blue a golden opportunity presented itself in the form of cooperation with Politecnico di Torino. The deal was the Poles had to develop a new advanced mathematical model of SOFC, whereas the Italians were to supply the all-important, good quality experimental data.

From the engineering point of view the most important is to have a mathematical model which gives reasonable results and can be used for design and device selection purposes. Processes occurring on cell surfaces, while important, must not take up an inordinate amount of attention. We used the full spectrum of mathematical modeling techniques—starting with deep investigation of basic principles and finishing with fully empirical models founded on artificial intelligence. Our work was mentioned by one of Springer's editors and a publishing proposal followed. This book took shape in what for us has been one short, giddy year. We condensed into it our experiences in the mathematical modeling of solid oxide fuel cells together with other power plant components. We would humbly welcome any suggestions for improving this book.

We ourselves have benefited from the many excellent books available on fuel cell technologies and modeling, inter alia [2–9]. Exploring ideas are our stock in trade and these other, for the most part, collections of works prepared by many co-authors offer a wide range of opinions, sometimes even within the same book.

This book—Advanced Modeling of Solid Oxide Fuel Cells—includes content for the efficient modeling of an array of devices from a single cell to whole hybrid systems. We also take a look at how to control solid oxide hybrid systems and set out valuable experience of experimental procedures and, more importantly, the results of research experiments.

The book is split into five chapters. The introduction contains general information about fuel cell technology, its history and possible applications. We highlight the pros and cons of SOFCs compared to other technologies. The second chapter gives theoretical background to the main principles in fuel cell modeling. Knowledge has been gleaned from many sources and only selected subjects are gone to provide some thermodynamics, chemical and fluid mechanics background. The third chapter seemed apt in the circumstances: advanced modeling techniques and artificial intelligence. Both aid a better understanding of the advanced techniques of modeling. The fourth chapter holds experimental data especially made for this book. Complete information about the experiments is provided: from description of the cell preparation procedure. Insights into fuel cell behavior come from the authors of the experiments. The fifth chapter describes and gives results of solid oxide fuel cell modeling in terms of both classical and advanced approaches. We fleshed this out by providing the basics on models of other system components, maintaining a clear separation between "design-point" and "off-design" model levels. The power of the models presented is illustrated by simulation results (e.g. a hybrid system, triple-generation, and bio-fuels utilization). At the end of the book a few appendices setting out thermodynamic and chemical tables used in model calculations as well as electrochemical impedance spectroscopy measurements results.

We included a few computational examples of related questions of modeling and touched on ways and procedures for the validation of models.

The book is a compendium of information for a wide range of researchers, engineers and other interested people to inform an understanding of the laws governing this area of energy source and to spread knowledge regarding the main advantages and limitations.

This book addresses the challenges involved in modeling solid oxide fuel cells and systems containing them. This book gives comprehensive and updated information on the principles of modeling SOFCs along with several practical examples. All modeling approaches presented here were based on reliable experimental data for SOFCs—obtained especially for the purposes of this book.

The book was written by two teams working in common purpose, one from the Institute of Heat Engineering at Warsaw University of Technology, the other from the Department of Energy at the University of Turin. Due care was taken to harmonize all pictures and graphs. For clarity, editorial staff adhered to agreed expressions and symbols and endeavored to avoid repeating information. All literature is cited in alphabetical order at the end of the book. We hope other like-minded souls will follow this approach in future.

This book is intended primarily for use by researchers, engineers and other technical people who wish to determine the basic performance of SOFCs through advanced computational methods and examine issues of combination with other power devices. While the content will inevitably age from the moment it is published, we hope it has a universal quality that will enable adaptation to new conditions.

Warsaw, September 2010 Jarosław Milewski

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