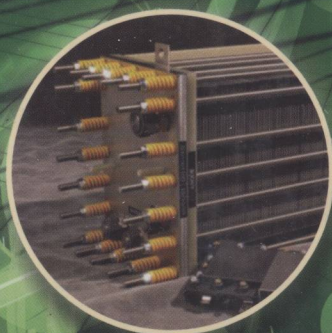
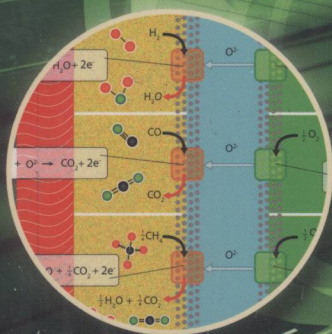


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# FUEL CELL FUNDAMENTALS

RYAN O'HAYRE • SUK-WON CHA • WHITNEY COLELLA • FRITZ B. PRINZ



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# FUEL CELL FUNDAMENTALS

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# FUEL CELL FUNDAMENTALS

To the parents who nurtured us.  
To the teachers who inspired us.

# PREFACE

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Imagine driving home in a fuel cell car with nothing but pure water dripping from the tailpipe. Imagine a laptop computer that runs for 30 hours on a single charge. Imagine a world where you plug your *house* into your *car* and power lines are a distant memory. These dreams motivate today's fuel cell research. While some dreams (like powering your home with your fuel cell car) may be distant, others (like a 30-hour fuel cell laptop) may be closer than you think.

By taking fuel cells from the dream world to the real world, this book teaches you the *science* behind the technology. This book focuses on the questions "*how*" and "*why*." Inside you will find straightforward descriptions of *how* fuel cells work, *why* they offer the potential for high efficiency, and *how* their unique advantages can best be used. Emphasis is placed on the fundamental scientific principles that govern fuel cell operation. These principles remain constant and universally applicable, regardless of fuel cell type or technology.

Following this philosophy, the first part, "Fuel Cell Principles," is devoted to basic fuel cell physics. Illustrated diagrams, examples, text boxes, and homework questions are all designed to impart a unified, *intuitive* understanding of fuel cells. Of course, no treatment of fuel cells is complete without at least a brief discussion of the practical aspects of fuel cell technology. This is the aim of the second part of the book, "Fuel Cell Technology." Informative diagrams, tables, and examples provide an engaging review of the major fuel cell technologies. In this half of the book, you will learn how to select the right fuel cell for a given application and how to design a complete system. Finally, you will learn how to assess the potential environmental impact of fuel cell technology.

Comments or questions? Suggestions for improving the book? Found a typo, think our explanations could be improved, want to make a suggestion about other important concepts to discuss, or have we got it all wrong? Please send us your feedback by emailing us at [fcf3@yahoogroups.com](mailto:fcf3@yahoogroups.com). We will take your suggestions into consideration for the next edition. Our website <http://groups.yahoo.com/group/fcf3> posts these discussions and additional educational materials. Thank you.

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# NOMENCLATURE

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Symbol	Meaning	Common Units
$A$	Area	$\text{cm}^2$
$A_c$	Catalyst area coefficient	Dimensionless
$a$	Activity	Dimensionless
ASR	Area specific resistance	$\Omega \cdot \text{cm}^2$
$C$	Capacitance	F
$C_{dl}$	Double-layer capacitance	F
$c^*$	Concentration at reaction surface	$\text{mol}/\text{cm}^2$
$c$	Concentration	$\text{mol}/\text{m}^3$
$c$	Constant describing how mass transport affects concentration losses	V
$c_p$	Heat capacity	$\text{J}/\text{mol} \cdot \text{K}$
$D$	Diffusivity	$\text{cm}^2/\text{s}$
$E$	Electric field	$\text{V}/\text{cm}$
$E$	Thermodynamic ideal voltage	V
$E_{\text{thermo}}$	Thermodynamic ideal voltage	V
$E_T$	Temperature-dependent thermodynamic voltage at reference concentration	V
$F$	Helmholtz free energy	J, J/mol
$F$	Faraday constant	96,485 C/mol
$F_k$	Generalized force	N
$f$	Reaction rate constant	$\text{Hz}, \text{s}^{-1}$
$f$	Friction factor	Dimensionless

Symbol	Meaning	Common Units
$G, g$	Gibbs free energy	J, J/mol
$g$	Acceleration due to gravity	m/s <sup>2</sup>
$\Delta G^\ddagger$	Activation energy barrier	J/mol, J
$\Delta G_{\text{act}}$	Activation energy barrier	J/mol, J
$H$	Heat	J
$H, h$	Enthalpy	J, J/mol
$H_C$	Gas channel thickness	cm
$H_E$	Diffusion layer thickness	cm
$h$	Planck's constant	$6.63 \times 10^{-34}$ J·s
$\hbar$	Reduced Planck constant, $h/2\pi$	$1.05 \times 10^{-34}$ J·s
$h_m$	Mass transfer convection coefficient	m/s
$i$	Current	A
$J$	Molar flux, Molar reaction rate	mol/cm <sup>2</sup> ·s
$\hat{j}$	Mass flux	g/cm <sup>2</sup> ·s, kg/m <sup>2</sup> ·s
$J_C$	Convective mass flux	kg/m <sup>2</sup> ·s
$j$	Current density	A/cm <sup>2</sup>
$j_0$	Exchange current density	A/cm <sup>2</sup>
$j_0^0$	Exchange current density at reference concentration	A/cm <sup>2</sup>
$j_L$	Limiting current density	A/cm <sup>2</sup>
$j_{\text{leak}}$	Fuel leakage current	A/cm <sup>2</sup>
$k$	Boltzmann's constant	$1.38 \times 10^{-23}$ J/K
$L$	Length	cm
$M$	Molar mass	g/mol, kg/mol
$\dot{M}$	Mass flow rate	kg/s
$M_{ik}$	Generalized coupling coefficient between force and flux	Varies
$m$	Mass	Kg
$mc_p$	Heat capacity flow rate	kW/kg·°C
$N$	Number of moles	Dimensionless
$N_A$	Avogadro's number	$6.02 \times 10^{23}$ mol <sup>-1</sup>
$n$	Number of electrons transferred in the reaction	Dimensionless
$n_g$	Number of moles of gas	Dimensionless
$P$	Power or power density	W or W/cm <sup>2</sup>
$P$	Pressure	bar, atm, Pa
$Q$	Heat	J, J/mol
$Q$	Charge	C
$Q_h$	Adsorption charge	C/cm <sup>2</sup>
$Q_m$	Adsorption charge for smooth catalyst surface	C/cm <sup>2</sup>
$q$	Fundamental charge	$1.60 \times 10^{-19}$ C
$R$	Ideal gas constant	8.314 J/mol·K
$R$	Resistance	$\Omega$
$R_f$	Faradaic resistance	$\Omega$

Symbol	Meaning	Common Units
Re	Reynolds number	Dimensionless
$S, s$	Entropy	J/K, J/mol · K
$S/C$	Steam-to-carbon ratio	Dimensionless
Sh	Sherwood number	Dimensionless
$T$	Temperature	K, °C
$t$	Thickness	cm
$U$	Internal energy	J, J/mol
$u$	Mobility	cm <sup>2</sup> /V · s
$\bar{u}$	Mean flow velocity	cm/s, m/s
$V$	Voltage	V
$V$	Volume	L, cm <sup>3</sup>
$V$	Reaction rate per unit area	mol/cm <sup>2</sup> · s
$v$	Velocity	cm/s
$v$	Hopping rate	s <sup>-1</sup> , Hz
$v$	Molar flow rate	mol/s, mol/min
$W$	Work	J, J/mol
$X$	Parasitic power load	W
$x$	Mole fraction	Dimensionless
$x_v$	Vacancy fraction	mol V/mol
$y_x$	Yield of element x	Dimensionless
$Z$	Impedance	$\Omega$
$z$	Height	cm

### Greek Symbols

Symbol	Meaning	Common Units
$\alpha$	Charge transfer coefficient	Dimensionless
$\alpha$	Coefficient for CO <sub>2</sub> equivalent	Dimensionless
$\alpha^*$	Channel aspect ratio	Dimensionless
$\beta$	Coefficient for CO <sub>2</sub> equivalent	Dimensionless
$\gamma$	Activity coefficient	Dimensionless
$\Delta$	Denotes change in quantity	Dimensionless
$\delta$	Diffusion layer thickness	m, cm
$\varepsilon$	Efficiency	Dimensionless
$\varepsilon_{FP}$	Efficiency of fuel processor	Dimensionless
$\varepsilon_{FR}$	Efficiency of fuel reformer	Dimensionless
$\varepsilon_H$	Efficiency of heat recovery	Dimensionless
$\varepsilon_O$	Efficiency overall	Dimensionless
$\varepsilon_R$	Efficiency, electrical	Dimensionless
$\varepsilon$	Porosity	Dimensionless
$\dot{\varepsilon}$	Strain rate	s <sup>-1</sup>

Symbol	Meaning	Common Units
$\eta$	Overtoltage	V
$\eta_{\text{act}}$	Activation overvoltage	V
$\eta_{\text{conc}}$	Concentration overvoltage	V
$\eta_{\text{ohmic}}$	Ohmic overvoltage	V
$\lambda$	Stoichiometric coefficient	Dimensionless
$\lambda$	Water content	Dimensionless
$\mu$	Viscosity	kg · m/s
$\mu$	Chemical potential	J, J/mol
$\tilde{\mu}$	Electrochemical potential	J, J/mol
$\rho$	Resistivity	$\Omega \text{ cm}$
$\rho$	Density	kg/cm <sup>3</sup> , kg/m <sup>3</sup>
$\sigma$	Conductivity	S/cm, ( $\Omega \cdot \text{cm}$ ) <sup>-1</sup>
$\sigma$	Warburg coefficient	$\Omega/\text{s}^{0.5}$
$\tau$	Mean free time	s
$\tau$	Shear stress	Pa
$\phi$	Electrical potential	V
$\phi$	Phase factor	Dimensionless
$\omega$	Angular frequency ( $\omega = 2\pi f$ )	rad/s

### Superscripts

Symbol	Meaning
0	Denotes standard or reference state
eff	Effective property

### Subscripts

Symbol	Meaning
diff	Diffusion
$E, e, \text{elec}$	Electrical (e.g., $P_e, W_{\text{elec}}$ )
$f$	Quantity of formation (e.g., $\Delta H_f$ )
(HHV)	Higher heating value
(LHV)	Lower heating value
$i$	Species $i$
$P$	Product
$P$	Parasitic
R	Reactant
rxn	Change in a reaction (e.g., $\Delta H_{\text{rxn}}$ )
SK	Stack
SYS	System

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