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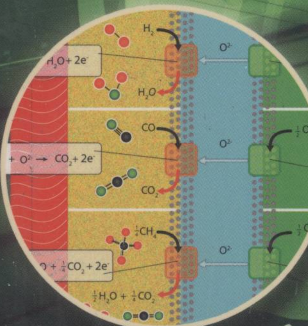
FUEL CELL FUNDAMENTALS

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



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To the parents who nurtured us.

To the teachers who inspired us.

PREFACE

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. 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

Symbol	Meaning	Common Units
A	Area	cm^2
A_c	Catalyst area coefficient	Dimensionless
a	Activity	Dimensionless
ASR	Area specific resistance	$\Omega \cdot cm^2$
C	Capacitance	F
C_{dl}	Double-layer capacitance	F
c^*	Concentration at reaction surface	mol/cm^2
c	Concentration	mol/m^3
c	Constant describing how mass transport affects concentration losses	V
c_p	Heat capacity	J/mol·K
D	Diffusivity	cm^2/s
E	Electric field	V/cm
E	Thermodynamic ideal voltage	V
E_{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	Hz, 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^2
$\Delta G^{\ddagger}$	Activation energy barrier	J/mol, J
ΔG_{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	6.63×10^{-34} J·s
$\hbar$	Reduced Planck constant, $h/2\pi$	1.05×10^{-34} J·s
h_m	Mass transfer convection coefficient	m/s
i	Current	A
J	Molar flux, Molar reaction rate	$mol/cm^2 \cdot s$
$\hat{J}$	Mass flux	$g/cm^2 \cdot s$, $kg/m^2 \cdot s$
J_C	Convective mass flux	$kg/m^2 \cdot s$
j	Current density	A/cm^2
j_0	Exchange current density	A/cm^2
j_0^0	Exchange current density at reference concentration	A/cm^2
j_L	Limiting current density	A/cm^2
j_{leak}	Fuel leakage current	A/cm^2
k	Boltzmann's constant	1.38×10^{-23} J/K
L	Length	cm
M	Molar mass	g/mol, kg/mol
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	6.02×10^{23} mol^{-1}
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^2
P	Pressure	bar, atm, Pa
Q	Heat	J, J/mol
Q	Charge	C
Q_h	Adsorption charge	C/cm^2
Q_m	Adsorption charge for smooth catalyst surface	C/cm^2
q	Fundamental charge	1.60×10^{-19} C
R	Ideal gas constant	8.314 J/mol·K
R	Resistance	Ω
R_f	Faradaic resistance	Ω

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	$cm^2/V \cdot s$
$\bar{u}$	Mean flow velocity	cm/s, m/s
V	Voltage	V
V	Volume	L, cm^3
V	Reaction rate per unit area	$mol/cm^2 \cdot s$
v	Velocity	cm/s
v	Hopping rate	s^{-1}, 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	Ω
z	Height	cm

Greek Symbols

Symbol	Meaning	Common Units
α	Charge transfer coefficient	Dimensionless
α	Coefficient for CO_2 equivalent	Dimensionless
α^*	Channel aspect ratio	Dimensionless
β	Coefficient for CO_2 equivalent	Dimensionless
γ	Activity coefficient	Dimensionless
Δ	Denotes change in quantity	Dimensionless
δ	Diffusion layer thickness	m, cm
ε	Efficiency	Dimensionless
ε_{FP}	Efficiency of fuel processor	Dimensionless
ε_{FR}	Efficiency of fuel reformer	Dimensionless
ε_{H}	Efficiency of heat recovery	Dimensionless
ε_{O}	Efficiency overall	Dimensionless
ε_{R}	Efficiency, electrical	Dimensionless
ε	Porosity	Dimensionless
$\dot{\varepsilon}$	Strain rate	s^{-1}

Symbol	Meaning	Common Units
η	Overvoltage	V
η_{act}	Activation overvoltage	V
η_{conc}	Concentration overvoltage	V
η_{ohmic}	Ohmic overvoltage	V
λ	Stoichiometric coefficient	Dimensionless
λ	Water content	Dimensionless
μ	Viscosity	kg · m/s
μ	Chemical potential	J, J/mol
$\tilde{\mu}$	Electrochemical potential	J, J/mol
ρ	Resistivity	Ω cm
ρ	Density	$\mathrm{kg/cm^3}$, $\mathrm{kg/m^3}$
σ	Conductivity	S/cm, $(\Omega \cdot \mathrm{cm})^{-1}$
σ	Warburg coefficient	$\Omega/\mathrm{s}^{0.5}$
τ	Mean free time	s
τ	Shear stress	Pa
ϕ	Electrical potential	V
ϕ	Phase factor	Dimensionless
ω	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, elec	Electrical (e.g., P_e, W_{elec})
f	Quantity of formation (e.g., ΔH_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., ΔH_{rxn})
SK	Stack
SYS	System

CONTENTS