NATURAL GAS RESERVOIR ENGINEERING

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PREFACE

This book presents concepts and applications of reservoir engineering principles essential to optimum development of natural gas reservoirs. It is based on courses taught at The University of Tulsa, The Pennsylvania State University, and adult education seminars in the United States and overseas.

The development of a natural gas field always depends on the reservoir and well characteristics as well as the equipment performance. A systems approach is emphasized throughout the book, since change in any component of the field production system will affect the performance of the other components. This book is arranged so that it can be used as a text or reference work for students and practicing engineers, geologists, and managers in the crude oil and natural gas production industry.

Chapter 1 discusses methods of estimating nonassociated, associated, and dissolved gas and abnormally pressured gas reserves. Reserves estimation and performance prediction for gas-condensate reservoirs are treated in Chapter 2. A comprehensive and rigorous treatment of production decline curve analysis is given in Chapter 3.

In Chapters 4 and 5 the theory and application of gas well testing are discussed. Well test analysis is an important subject in reservoir engineering, since it enables us to obtain reservoir parameters that could be used to predict future reservoir performance. Chapter 4 considers deliverability or back-pressure testing of gas wells. Chapter 5 discusses pressure transient analysis for gas wells. Both the pressure-squared technique and the pseudo-pressure function or real gas potential technique are treated and compared.

The systems approach is used to determine optimum gas field development strategies in Chapter 6; examples of reservoir performance techniques and field development patterns are presented. Chapter 7 extends some of the techniques of gas transmisison and gas reservoir engineering to the storage of natural gas.

Much of the material on which this book is based was drawn from the publications of the Society of Petroleum Engineers of the American Institute of Mining, Metallurgical and Petroleum Engineers, the American Gas Association, the Division of Production of the American Petroleum Institute, and the Gas Processors Suppliers Association. Tribute is due to these organizations and also to a host of schools and authors who sponsor programs and have contributed to petroleum literature in various other publications.

I am indebted to my students, whose enthusiasm for the subject has made teaching a pleasure. To my colleagues who have adopted this material in various petroleum and natural gas engineering departments in the United States and overseas, I express my gratitude for their constructive criticisms and comments that became textbook inputs. I thank Peggy Conrad for typing the manuscript.

I would like to express my appreciation to the editorial staff of John Wiley, including Merrill Floyd and Deborah Herbert, for their patience and politeness. I thank Cindy Stein-Lapidus and the members of Wiley's production staff for a fine job.

Chi U. Ikoku

NOMENCLATURE

QUANTITIES IN ALPHABETICAL ORDER

(*) Dimensions: L = length, m = mass, q = electrical charge, t = time, and T = temperature.
(**) To avoid conflicting designation in some cases, use of reserve symbols and reserve subscripts is permitted.

Quantity	SPE Standard	Reserve SPE Letter Symbols**	Dimensions*
air requirement	a	F_a	
angle	α alpha	β beta	
angle	θ theta	γ gamma	
angle, contact	θ_c theta	γ_c gamma	
angle of dip	α_d alpha	θ_d theta	
area	A	S	L^2
Arrhenius reaction rate velocity constant	w	z	L^3/m
breadth, width, or (primarily in fracturing) thickness	b	w	L
burning-zone advance rate	v_b	V_b, u_b	L/t
capillary pressure	P_c	P_c, p_c	m/Lt^2
charge	Q	q	q
coefficient, convective heat transfer	h	h_h, h_T	m/t^3T
coefficient, heat transfer, interphase convective (use h, or convective coefficient symbol, with pertinent phase subscripts added)			m/t³T
coefficient, heat transfer, overall	U	U_T, U_θ	m/t^3T
coefficient, heat transfer, radiation	I	I_T, I_θ	m/t^3T
components, number of	C	n_c	
compressibility	c	k, κ kappa	Lt^2/m
compressibility factor	z	Z	
concentration	C	c, n	various

Courtesy of Society of Petroleum Engineers of
American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc.

Quantity	SPE Standard	Reserve SPE Letter Symbols**	Dimensions*
condensate or natural gas liquid content	C_L	c_L, n_L	various
conductivity	σ sigma	γ gamma	various
conductivity, thermal (always with additional phase or system subscripts)	k_h	λ lambda	mL/t^3T
contact angle	θ_c theta	γ_c gamma	
damage ratio ("skin" conditions relative to formation conditions unaffected by well operations)	F_s	F_d	
density	ρ rho	D	m/L^3
depth	D	y, H	L
diameter	d	D	L
diffusion coefficient	D	μ mu, δ delta	L^2/t
dimensionless fluid influx function, linear aquifer	Q_{LtD}	Q_{ltD}	
dispersion coefficient	K	d	L^2/t
displacement	s	L	L
displacement ratio	δ delta	F_d	
distance between adjacent rows of injection and production wells	d	L_d, L_2	L
distance between like wells (injection or production) in a row	a	L_a, L_1	L
distance, length, or length of path	L	s, l script l	L
efficiency	E	η eta, e	
electrical resistivity	ρ rho	R	mL^3/tq^2
electromotive force (voltage)	E	V	mL^2/t^2q
elevation referred to datum	Z	D, h	L
encroachment or influx rate	e	i	L^3/t
energy	E	U	mL^2/t^2
enthalpy (always with phase or system subscripts)	H	I	mL^2/t^2
enthalpy (net) of steam or enthalpy above reservoir temperature	H_s	I_s	mL^2/t^2
enthalpy, specific	h	i	L^2/t^2
entropy, specific	s	σ sigma	L^2/t^2T
entropy, total	S	σ_t sigma	mL^2/t^2T
equilibrium ratio	K	k, F_{eq}	
fluid influx function, linear aquifer, dimensionless	Q_{LtD}	Q_{ltD}	
flow rate or flux, per unit area (volumetric velocity)	u	ψ psi	L/t
flow rate or production rate	q	Q	L^3/t
fluid (generalized)	F	f	various
flux	u	ψ psi	various
force	F	Q	mL/t^2
formation volume factor	B	F	
fraction gas	f_g	F_g	
fraction liquid	f_L	F_L, f_l	
frequency	f	ν nu	l/t

Quantity	SPE Standard	Reserve SPE Letter Symbols**	Dimensions*
fuel consumption	m	F_F	various
fuel deposition rate	N_R	N_F	m/L^3t
gas (any gas, including air)—always with identifying subscripts	G	g	various
gas in place in reservoir, total initial	G	g	L^3
gas-oil ratio, producing (if needed, the reserve symbols could be applied to other gas-oil ratios)	R	F_g, F_{go}	
general and individual bed thickness	h	d, e	L
gradient	g	γ gamma	various
heat flow rate	Q	q, Φ phi_{cap}	mL^2/t^3
heat of vaporization, latent	L_v	λ_v lambda	L^2/t^2
heat or thermal diffusivity	α alpha	α, η_h eta	L^2/t
heat transfer coefficient, convective	h	h_h, h_T	m/t^3T
heat transfer coefficient, interphase convection (use h, or convective coefficient symbol with pertinent subscripts added)			m/t^3T
heat transfer coefficient, over-all	U	U_T, U_θ	m/t^3T
heat transfer coefficient, radiation	I	I_T, I_θ	m/t^3T
height (elevation)	Z	D, h	L
height (other than elevation)	h	d, e	L
hydraulic radius	r_H	R_H	L
index of refraction	n	μ mu	
influx (encroachment) rate	e	i	L^3/t
influx function, fluid, linear aquifer, dimensionless	Q_{LtD}	Q_{ltD}	
initial water saturation	S_{wi}	ρ_{wi} rho, S_{wi}	
injectivity index	I	i	L^4t/m
intercept	b	Y	various
interfacial or surface tension	σ sigma	y, γ gamma	m/t^2
interstitial-water saturation in oil band	S_{wo}	S_{wb}	
irreducible water saturation	S_{iw}	ρ_{iw} rho, S_{iw}	
kinematic viscosity	ν nu	N	L^2/t
length	L	s, l script l	L
length, path length, or distance	L	s, l script l	L
mass flow rate	w	m	m/t
mobility ratio	M	F_λ	
mobility ratio, diffuse-front approximation, $[(\lambda_D + \lambda_d)_{swept}/(\lambda_d)_{unswept}]$; D signifies displacing; d signifies displaced; mobilities are evalaluated at average saturation conditions behind and ahead of front	$M_{\bar{S}}$	M_{Dd}, M_{su}	
mobility ratio, sharp-front approximation, (λ_D/λ_d)	M	F_λ	
mobility ratio, total, $[(\lambda_t)_{swept}/(\lambda_t)_{unswept}]$; "swept" and "unswept" refer to invaded and uninvaded regions behind and ahead of leading			

Quantity	SPE Standard	Reserve SPE Letter Symbols**	Dimensions*
edge of a displacement front	M_t	$F_{\lambda t}$	
mobility, total, of all fluids in a particular region of the reservoir; e.g., $(\lambda_o + \lambda_g + \lambda_w)$	λ_t lambda	Λ lambda$_{cap}$	L^3t/m
modulus, bulk	K	K_b	m/Lt^2
modulus of elasticity in shear	G	E_s	m/Lt^2
modulus of elasticity (Young's modulus)	E	Y	m/Lt^2
mole fraction gas	f_g	F_g	
mole fraction liquid	f_L	F_L, f_l	
molecular refraction	R	N	L^3
moles, number of	n	N	
moles of liquid phase	L	n_L	
moles of vapor phase	V	n_v	
moles, total	n	n_t, N_t	
number (of moles, or components, or wells, etc.)	n	N	
oil (always with identifying subscripts)	n	n	various
oil in place in reservoir, initial	N	n	L^3
oxygen utilization	e_{O_2}	E_{O_2}	
path length, length, or distance	L	s, $\mathcal{l}$ script l	L
permeability	k	K	L^2
Poisson's ratio	μ mu	ν nu, σ sigma	
porosity	ϕ phi	f, ε epsilon	
pressure	p	P	m/Lt^2
production rate or flow rate	q	Q	L^3/t
productivity index	J	j	L^4t/m
quality (usually of steam)	f_s	Q, x	
radial distance	Δr	ΔR	L
radius	r	R	L
radius, hydraulic	r_H	R_H	L
ratio, damage ("skin" conditions relative to formation conditions unaffected by well operations)	F_s	F_d	
ratio initial reservoir free gas volume to initial reservoir oil volume	m	F_{Fo}, F_{go}	
ratio, mobility	M	F_λ	
ratio, mobility, diffuse-front approximation, $[(\lambda_D + \lambda_d)_{swept}/(\lambda_d)_{unswept}]$; D signifies displacing; d signifies displaced; mobilities are evaluated at average saturation conditions behind and ahead of front	$M_{\bar{S}}$	M_{Dd}, M_{su}	
ratio, mobility, sharp-front approximation, (λ_D/λ_d)	M	$F\lambda$	
ratio, mobility, total, $[(\lambda_t)_{swept}/(\lambda_t)_{unswept}]$; "swept" and "unswept" refer to invaded and uninvaded regions behind and ahead of leading edge of a displacement front	M_t	$F_{\lambda t}$	
reaction rate constant	k	r, j	L/t

Quantity	SPE Standard	Reserve SPE Letter Symbols**	Dimensions*
reciprocal formation volume factor, volume at standard conditions divided by volume at reservoir conditions	b	f, F	
reciprocal permeability	j	ω omega	$1/L^2$
resistance	r	R	mL^2/tq^2
resistance	r	R	various
resistivity, electrical	ρ rho	R	mL^3/tq^2
saturation	S	ρ rho, s	
saturation, water, initial	S_{wi}	ρ_{wi} rho, s_{wi}	
saturation, water, irreducible	S_{iw}	ρ_{iw} rho, s_{iw}	
skin effect	s	S, σ sigma	
skin (radius of well damage or stimulation)	r_s	R_s	L
slope	m	A	various
specific gravity	γ gamma	s, F_s	
specific heat (always with phase or system subscripts)	C	c	L^2/t^2T
specific heats ratio	γ gamma	k	
specific injectivity index	I_s	i_s	L^3t/m
specific productivity index	J_s	j_s	L^3t/m
specific volume	v	v_s	L^3/m
specific weight	F_{wv}	γ gamma	m/L^2T^2
stimulation radius of well (skin)	r_s	R_s	L
strain, normal and general	ε epsilon	e, ε_n epsilon	
strain, shear	γ gamma	ε_s epsilon	
strain, volume	θ theta	θ_v theta	
stress, normal and general	σ sigma	s	m/Lt^2
stress, shear	τ tau	s_s	m/Lt^2
surface tension	σ sigma	y, γ gamma	m/t^2
temperature	T	θ theta	T
thermal conductivity (always with additional phase or system subscripts)	k_h	λ lambda	mL/t^3T
thermal cubic expansion coefficient	β beta	b	$1/T$
thermal or heat diffusivity	α alpha	a, η_b eta	L^2/t
thickness (general and individual bed)	h	d, e	L
time	t	τ tau	t
total mobility of all fluids in a particular region of the reservoir; e.g., $(\lambda_o + \lambda_g + \lambda_w)$	λ_t lambda	Λ lambda_{cap}	L^3t/m
total mobility ratio, $[(\lambda_t)_{swept}/(\lambda_t)_{unswept}]$; "swept" and "unswept" refer to invaded and uninvaded regions behind and ahead of leading edge of a displacement front	M_t	$F_{\lambda t}$	
transfer coefficient, convective heat	h	h_h, h_T	m/t^3T
transfer coefficient, heat, interphase convective (use h, or convective coefficient symbol with pertinent phase subscripts added)			m/t^3T
transfer coefficient, heat, overall	U	U_T, U_θ	m/t^3T

Quantity	SPE Standard	Reserve SPE Letter Symbols**	Dimensions*
transfer coefficient, heat, radiation	I	I_T, I_θ	m/t^3T
utilization, oxygen	e_{o_2}	E_{o_2}	
velocity	v	V, u	$1L/t$
viscosity	μ mu	η eta	m/Lt
volume	V	v	L^3
volumetric velocity (flow rate or flux, per unit area)	u	ψ psi	L/t
water (always with identifying subscripts)	W	w	various
water in place in reservoir, initial	W	w	L^3
water saturation, initial	S_{wi}	ρ_{wi} rho, s_{wi}	
water saturation, irreducible	S_{iw}	ρ_{iw} rho, s_{iw}	
wave number	σ sigma	$\bar{v}$	$1/L$
weight	W	w, G	mL/t^2
wet-gas content	C_{wg}	c_{wg}, n_{wg}	various
width, breadth, or (primarily in fracturing) thickness	b	w	L
work	W	w	mL^2/t^2

Subscripts

Subscript	SPE Standard	Reserve SPE Letter Subscripts**
air	a	A
atmospheric	a	A
average or mean saturation	$\bar{S}$	$\bar{\rho}$ rho, $\bar{s}$
band or oil band	b	B
base	b	r, β beta
boundary conditions, external	e	o
breakthrough	BT	bt
bubble point or saturation	b	s
burned or burning	b	B
calculated	C	calc
capillary (usually with capillary pressure, P_c)	c	C
casing or casinghead	c	cg
contact (usually with contact angle, θ_c)	c	C
core	c	C
cumulative influx (encroachment)	e	i
damage or damaged (includes "skin" conditions)	s	d
depleted region, depletion	d	δ delta
dispersed	d	D
dispersion	K	d
displaced	d	s, D
displacing or displacement	D	s, σ sigma

Subscript	SPE Standard	Reserve SPE Letter Subscripts**
entry	e	E
equivalent	eq	EV
estimated	E	est
experimental	E	EX
fill-up	F	f
finger or fingering	f	F
flash separation	f	F
fraction or fractional	f	r
fracture, fractured, or fracturing	f	F
free (usually with gas or gas-oil ratio quantities)	F	f
front, front region, or interface	f	F
gas	g	G
gross	t	T
heat or thermal	h	T, θ theta
hole	h	H
horizontal	H	h
hydrocarbon	h	H
imbibition	I	i script i
influx (encroachment), cumulative	e	i
injected, cumulative	i	I
injection, injected, or injecting	i	inj
inner or interior	i	ι iota, i script i
interface, front region, or front	f	F
interference	I	i, i script i
invaded	i	I
invaded zone	i	I
invasion	I	i
irreducible	i	i script i, ι iota
linear, lineal	L	I script I
liquid or liquid phase	L	I script I
lower	I script I	L
mean or average saturation	$\bar{S}$	$\bar{\rho}$ rho, $\bar{s}$
mixture	M	m
mobility	λ lambda	M
nonwetting	nw	NW
normalized (fractional or relative)	n	r, R
oil	o	n
outer or exterior	e	o
permeability	k	K
pore (usually with volume, V_p)	p	P
production period (usually with time, t_p)	p	P
radius, radial, or radial distance	r	R
reference	r	b, ρ rho
relative	r	R
reservoir	R	r

Subscript	SPE Standard	Reserve SPE Letter Subscripts**
residual	r	R
saturation, mean or average	$\bar{S}$	$\bar{\rho}$ rho, $\bar{s}$
saturation or bubble point	b	s
segregation(usually with segregation rate, q_s)	s	S, σ sigma
shear	s	τ tau
skin (stimulation or damage)	s	S
slip or slippage	s	σ sigma
solid(s)	s	σ sigma
stabilization (usually with time)	s	S
steam or steam zone	s	S
stimulation (includes "skin" conditions)	s	S
storage or storage capacity	S	S, σ sigma
strain	ε epsilon	e
surface	s	σ sigma
swept or swept region	s	S, σ sigma
system	s	σ sigma
temperature	T	h, θ theta
thermal (heat)	h	T, θ theta
total, total system	t	T
transmissibility	T	t
treatment or treating	t	τ tau
tubing or tubing head	t	tg
unswept or unswept region	u	U
upper	u	U
vaporization, vapor, or vapor phase	v	V
velocity	v	V
vertical	V	v
volumetric or volume	V	v
water	w	W
weight	W	w
wellhead	wh	th
wetting	w	W

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