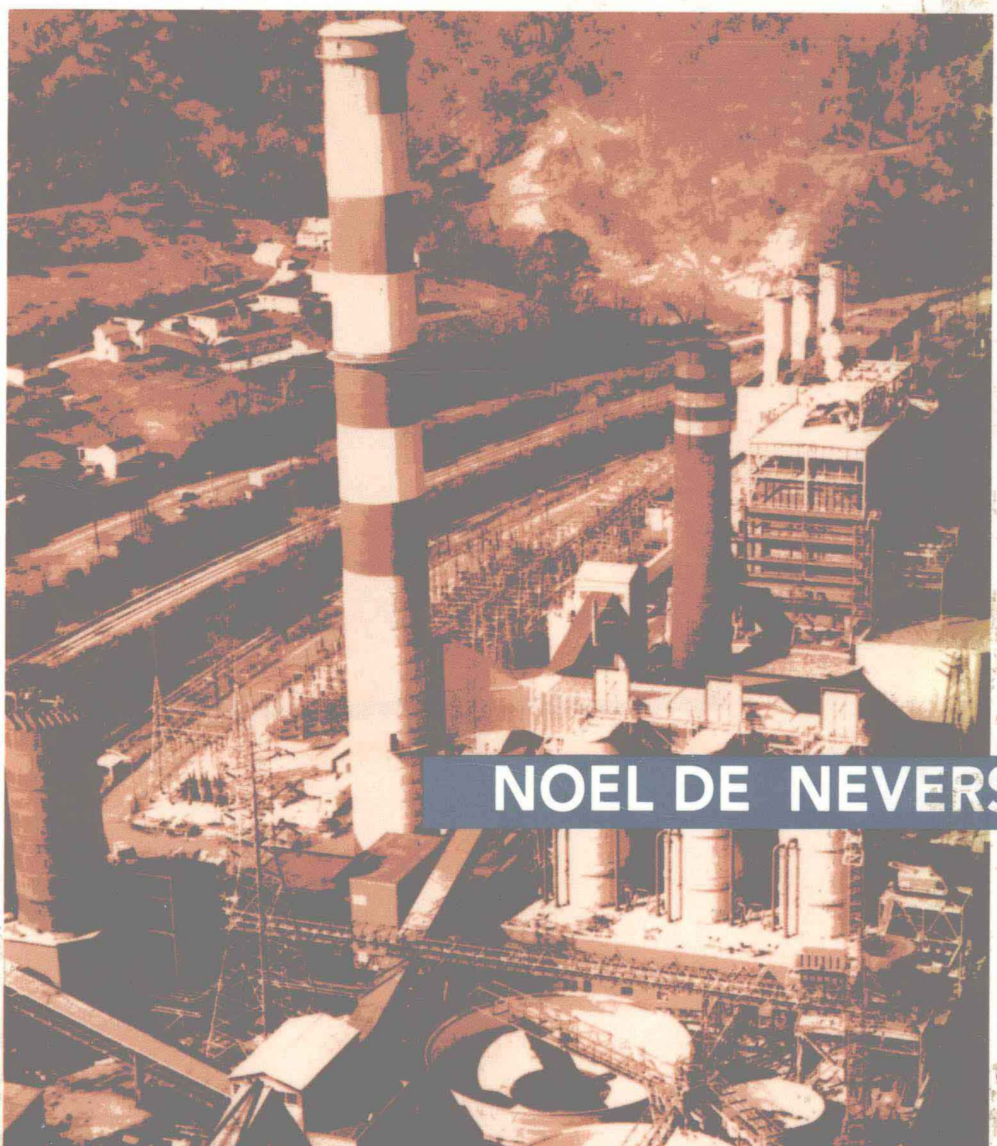
AIR POLLUTION CONTROL ENGINEERING



NOEL DE NEVERS

AIR POLLUTION CONTROL ENGINEERING

Noel de Nevers
University of Utah

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AIR POLLUTION CONTROL ENGINEERING

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ABOUT THE AUTHOR

Noel de Nevers received a B.S. from Stanford University in 1954, and M.S. and Ph.D. degrees from the University of Michigan in 1956 and 1959, all in chemical engineering.

He worked for the research arms of what is now called the Chevron Oil Company from 1958 to 1963 in the areas of chemical process development, chemical and refinery process design, and secondary recovery of petroleum. He has been on the faculty of the University of Utah from 1963 to the present in the Department of Chemical Engineering. (The latter became the Department of Chemical and Fuels Engineering, by merger, in 1992.)

He has worked for the National Reactor Testing Site, Idaho Falls, Idaho, on nuclear problems, for the U.S. Army Harry Diamond Laboratory, Washington, DC, on weapons, and for the Office of Air Programs of the U.S. EPA in Durham, NC, on air pollution.

He was a Fulbright student of Chemical Engineering at the Technical University of Karlsruhe, West Germany, in 1954–1955, and a Fulbright lecturer on Air Pollution at the Universidad del Valle, in Cali, Colombia, in the summer of 1974.

He was a member of the Utah Air Conservation Committee (the state's air pollution control board) from 1972 to 1984 and its chair in 1983–1984. He served on the Utah Governor's Citizen Advisory Task Force on the Protection of Visibility in 1986, the Utah Legislature's Hazardous Waste Task Force in 1988, and the Utah Governor's Clean Air Commission in 1989–1990. He is currently on the Western Governor's Conference Grand Canyon Visibility Transport Commission Citizen's Advisory Board.

His areas of research and publication are in fluid mechanics, thermodynamics, air pollution, technology and society, energy and energy policy, and explosions and fires. He regularly consults on air pollution problems, explosions, and fires.

In 1991, his textbook, *Fluid Mechanics for Chemical Engineers,* Second Edition was issued by McGraw-Hill.

In 1993 he received the Corcoran Award from the Chemical Engineering Division of the American Society for Engineering Education for the best paper (" 'Product in the Way' Processes") that year in *Chemical Engineering Education.*

In addition to his serious work he has three "de Nevers's Laws" in the latest "Murphy's Laws" compilation, and won the title "Poet Laureate of Jell-O Salad" at the Last Annual Jell-O Salad Festival in Salt Lake City in 1983.

PREFACE

This book is intended for university seniors and graduate students who would like an overview of air pollution control engineering. It may be of value as a reference work to engineers who are professionally active in air pollution control, but they will probably find the treatment somewhat simpler and less detailed than their own personal experience. They may, however, find use for the treatment of areas in which they are not personally experienced.

About half of the book is devoted to control devices, their theory and practice. The other half is devoted to topics that form some of the background for the selection of such devices, e.g., air pollution effects, the structure of U.S. air pollution law, atmospheric models, etc. These topics interact strongly with the device selection and design, which is the reason for their inclusion.

I have tried to make the book direct and clear enough that an experienced engineer can read and understand any part of it without help. I have also tried to base it as completely as possible on the basic chemical engineering disciplines of stoichiometry, thermodynamics, fluid mechanics, heat transfer, mass transfer, and reaction kinetics so that senior students in chemical engineering will see that this is a field in which they can use all that they have previously learned. I have also tried to select the level of treatment so that any interested chemical engineering faculty member can teach a senior level course using the book (and the solutions manual) without requiring that the faculty member have a personal background in air pollution control engineering. The chemistry in this book is presented at a level corresponding to a background of one year of university chemistry because when I teach our course there are mechanical and civil engineering students present, who have that chemistry background.

I have been guided by two pedagogical maxims: "The three rules of teaching are, from the known to the unknown, from the simple to the complex, one step at a time," and "If you don't understand something at least two ways, you don't understand it." I have devoted more space and effort to determining numerical values of pertinent quantities than do most authors. I believe students need to develop a feel for how big? how fast? how hot? and how much?

In many areas of the book the treatment in the text is simple, with a more complex treatment outlined or discussed in one of the problems. Students are encouraged at least to read through all the problems, to see where more complex and complete treatments are either described or referred to. In many places in the book there are digressions not directly applicable to air pollution and problems not directly related to air pollution. Some of these are there because they show interesting related technical issues that do not apply directly to air pollution control. I include these because I think they help students build mental bridges to other parts of their personal experiences. The more the students are able to integrate the new information in this book into their existing knowledge base by such connections, the more likely they are to retain it and be able to use it.

I will be very grateful to readers who point out to me typographic errors, incorrect equation numbers, incorrect figure numbers, or simply errors of any kind. Such errors will be corrected in subsequent editions or printings.

I would like to thank the following reviewers for their many helpful comments and suggestions: Candis Claiborn, Washington State University; Cliff George, Mississippi State University; and Lt. Col. W. Chris King, United States Military Academy.

Noel de Nevers

NOTATION

Symbol	Brief Description	Units	
		English	SI
A	coal ash content	wt %	wt %
A	area	ft^2	m^2
A	area of city = LW	ft^2	m^2
A	constant in Antoine equation	—	—
A	constant in Arrhenius equation (sometimes called "frequency factor")	1/s	1/s
A	constant in Cunningham correction factor	—	—
a	acceleration	ft/s^2	m/s^2
a	length parameter	1/ft	1/m
a	mass transfer area per unit volume	ft^2/ft^3	m^2/m^3
A, B, C	chemical species in reaction rate equations	—	—
A/F	air fuel ratio	lbm/lbm	kg/kg
A, B, C, K	arbitrary constants	various	various
a, b	characteristic dimensions	—	—
a, b	polynomial coefficients	various	various
b	background concentration	not used	μg/m^3
b	time parameter	1/h	1/s
B, C	constants in Antoine equation	°R	°C or K
C	carbon content of fuel	wt %	wt %
C	Cunningham correction factor	—	—
C_d	drag coefficient	—	—
C_P	heat capacity at constant pressure	Btu/(lbm or lbmol) · °F	J/(kg or mol) · °C
C_V	heat capacity at constant volume	Btu/(lbmol or lbm) · °F	J/(kg or mol) · °C

c	concentration	(lbm or lbmol)/ft^3	(kg or mol)/m^3
$\mathcal{D}$	diffusivity	ft^2/s	m^2/s
D	diameter or particle diameter	ft	m
D_a or D_{pa}	aerodynamic diameter, or aerodynamic diameter of a drop or particle	not used	$\mu(\text{g/cm}^3)^{0.5}$
D_b	diameter of barrier	ft	m
D_{cut}	"cut diameter," the diameter at which the efficiency = 50%	ft	m
D_D	droplet diameter	ft	m
D_{mean}	mean particle diameter (arithmetic or logarithmic)	ft	m
D_o	outside diameter of a cyclone separator	ft	m
D_p	particle diameter	ft	m
E	electric field strength	V/ft	V/cm
E	excess air	lbmol/lbmol	mol/mol
E_A	activation energy	Btu/lbmol	kcal/mol
E_o	electric field strength where particles are charged	V/ft	V/cm
E_p	electric field strength where particles are collected	V/ft	V/cm
EF	emission factor	various	various
F	force	lbf	N
F	packing factor in flooding equation, or packing factor for absorbers	—	—
F_d	drag force	lbf	N
F_g	gravity force	lbf	N
f	fugacity (for ideal gases, = partial pressure)	psia	Pa
f_s	saturated fugacity at this T ($\approx$ vapor pressure)	psia	Pa
G	Gibbs free energy	Btu/lbmol	J/mol
G	molar flow of nontransferred component in gas phase	lbmol/s	mol/s
G_m	molar mas velocity	lbmol/ft$^2\cdot$ s	mol/m$^2\cdot$ s
G'	gas mass velocity	lb/ft$^2\cdot$ s	kg/m$^2\cdot$ s
g	acceleration of gravity	ft/s^2	m/s^2
H	effective stack height	ft	m
H	height in the vertical direction, or the direction in which particles are collected	ft	m
H	Henry's law constant	atmospheres	Pa
H	humidity, lbm water/lbm dry air	—	—
H	hydrogen content of fuel	wt %	wt %
H	mixing height	ft	m
h	enthalpy or molar enthalpy	Btu/(lbm or lbmol)	J/(kg or mol)
h	height above floor in a gravity settler	ft	m
h	height of slit	ft	m
h	physical stack height	ft	m
Δh	plume rise	ft	m
j_m	mass transfer factor	—	—
K	coefficient in pressure drop equations	—	—
K	constant in Langmuir equation	1/atm	1/Pa
K	equilibrium constant	various	various
K	turbulent dispersion coefficient	ft^2/s	m^2/s

K	mass transfer coefficient	lbmol/ft^2· s	mol/m^2· s
K_p	equilibrium constant with activities in atm	various	various
k	Boltzmann constant = R/Avogadro's number	not used	1.38×10^{-23} kg · m^2/K · s^2
k	coefficient in modified Deutsch-Anderson equation	—	—
k	kinetic rate constant	various	various
k	permeability	ft^2	m^2
k	ratio of specific heats (C_P/C_V)	—	—
k	reaction velocity constant	1/s	1/s
k_f, k_b	forward and backward reaction rate constants	various	various
k'_g	mass transfer coefficient	lbmol/ft^2· s	mol/m^2· s
L	length	ft	m
L	length of city in downwind direction (in box models)	ft	m
L	length of collector in flow direction	ft	m
L	length of piston stroke	in.	m
L	mixing height (Fig. 6.9 only)	not used	m
L	molar flow of nontransferred component in liquid phase	lbmol/s	mol/s
L'	liquid mass velocity	lb/ft^2· s	kg/m^2· s
L_V	visual range constant	not used	km · μg/m^3
M	molecular weight	lbm/lbmol	g/mol
m	mass	lbm	kg
$\dot{m}$	mass flow rate	lbm/s	kg/s
N	nitrogen content of fuel	wt %	wt %
N	number of particles, or of people, or of turns in a cyclone separator	—	—
N	number, number of transfer units	—	—
N_D	rate of droplet flow	number/s	number/s
N_s	Separation number = Characteristic dimension/Stokes stopping number [see Section 8.2]	—	—
n	exponent in rate equation and Freundlich equation	—	—
n	age	year	year
n	distance in direction of interest	ft	m
n	exponent in series expansion	—	—
n	number of mols	lbmol	mol
$\dot{n}$	molar flow rate	lbmol/s	mol/s
O	oxygen content of fuel	wt %	wt %
pH	negative $\log_{10}$ of the H^+ activity (≈ concentration) expressed in mol/liter	—	—
P	gas pressure	psia or atmospheres	Pa or mb
Po	power	ft · lbf/s or hp	kW
p	penetration = 1− collection efficiency	—	—
p	vapor pressure	psia	Pa
p_{water}	vapor pressure of liquid water	psia	Pa or mb
Q	emission rate	lbm/s	g/s
Q	volumetric flow rate = $V \cdot A$	ft^3/s	m^3/s
Q_G	gas volumetric flow rate	ft^3/s	m^3/s

Q_L	liquid volumetric flow rate	ft^3/s	m^3/s
q	charge on a particle	C	C
q	emission rate per unit area	lbm/hr · mi^2	g/s · m^2
$\mathscr{R}$	Reynolds number	—	—
$\mathscr{R}_p$	Reynolds number for particles	—	—
RH	Relative humidity $= \dfrac{\text{Humidity}}{\text{Saturation humidity}}$	—	—
R	universal gas constant (See Appendix A)	psi · ft^3/lbmol · °R	N · m/mol · K
r	radius	ft	m
r	reaction rate	various	various
S	sulfur content of fuel	wt %	wt %
Sc	Schmidt number	—	—
s	standard deviation	various	various
T	absolute temperature	°R	K
t	quench zone thickness	in.	m
t	thickness	ft	m
t	time	s	s
$t_{1/2}$	half-life	s	s
U	overall heat transfer coefficient	Btu/h · °F · ft^2	W/m^2 · K
u	wind speed	ft/s	m/s
u	internal energy or molar internal energy	Btu/(lbm or lbmol)	J/(kg or mol)
V	voltage (or potential)	V	V
V	volume	ft^3	m^3
V	velocity	ft/s	m/s
V_{avg}	average gas velocity	ft/s	m/s
V_c	particle or gas velocity on a circular path	ft/s	m/s
V_D	drop velocity	ft/s	m/s
$V_{D\text{-fixed}}$	drop velocity relative to fixed coordinates	ft/s	m/s
V_G	gas velocity	ft/s	m/s
V_{rel}	relative velocity	ft/s	m/s
V_S	stack gas velocity	ft/s	m/s
V_S	superficial velocity	ft/s	m/s
V_t	terminal velocity	ft/s	m/s
W	mass of solids/(volume of gas × cake density)	—	—
W	width of a collecting device	ft	m
W	width of city	ft	m
w	drift velocity (in electrostatic precipitators)	ft/s	m/s
w	weight fraction	—	—
w	weight of a particle sample	lbm	kg
w^*	equilibrium amount adsorbed	lbm/lbm	kg/kg
[X]	activity or concentration of compound X	not used	atm, or mol/cm^3
X	molar humidity of air, mol water/mol dry air	—	—
X	amount emitted in Lagrangian Gaussian plume equations	lb	kg
X	liquid content of transferred component	lbmol/lbmol	mol/mol
x	distance	ft	m

x	independent variable	various	various
x	mol fraction in the liquid phase	—	—
x	mol number of carbon in hydrocarbon fuel	—	—
x	small quantity in series expansion	—	—
x_{mean}	mean value of independent variable	various	various
x, y	distance in x and y directions	ft	m
x, y	indices in hydrocarbon formulae, $\mathrm{C_xH_y}$	—	—
x, y, z	coordinate directions or lengths	ft	m
Y	gas content of transferred component	lbmol/lbmol	mol/mol
y	mol fraction in gas or vapor	—	—
y	mol number of hydrogen in hydrocarbon fuel	—	—
y^*	equilibrium mol fraction	—	—
z	elevation or vertical distance	ft	m
z	mol number of oxygen deficiency	—	—
z	number of standard deviations from mean, $= (x - x_{\text{mean}})/\sigma$ in the normal distribution, $= [\ln(D/D_{\text{mean}})]/\sigma$ in the log normal distribution.	—	—
α	constant defined by Eq. (12.17)	1/s	1/s
α	constant in Freundlich equation	mixed	mixed
α	filter medium resistance	ft	m
α	dummy variable in flooding equation	—	—
β	dummy variable in flooding equation	—	—
ε	dielectric constant	—	—
ε	porosity	—	—
ε_O	permittivity of free space	not used	8.85×10^{-12} C/V · m or 8.85×10^{-12} F/m
Φ	cumulative distribution function	—	—
ϕ	equivalence ratio	—	—
ϕ	latitude	deg	deg
η	efficiency	—	—
λ	latent heat of vaporization	Btu/lbm	J/kg
λ	mean free path	ft	m
λ	reciprocal of equivalence ratio	—	—
λ	wavelength of maximum emission	(never used)	μm
μ	micron or micrometer	not used	$= 10^{-6}$ m
μ	viscosity	cP	Pa · s
ν	kinematic viscosity $= \mu/\rho$	$\mathrm{ft^2/s}$	$\mathrm{m^2/s}$
ρ	density or molar density	(lbm or lbmol)/$\mathrm{ft^3}$	(kg or mol)/$\mathrm{m^3}$
ρ'_L	liquid density at normal boiling point	$\mathrm{lbm/ft^3}$	$\mathrm{kg/m^3}$
σ	$(\text{variance})^{0.5}$	various	various
σ	constant in Gaussian, or normal, distribution function	various	various
σ	Stefan-Boltzmann constant	Btu/hr · $\mathrm{ft^2}$ · $\mathrm{°R^4}$	W/$\mathrm{m^2}$ · $\mathrm{K^4}$
σ_y	horizontal dispersion coefficient	not used	m
σ_z	vertical dispersion coefficient	not used	m
Ψ	ratio of density to water density in flooding equation	—	—
ω	angular velocity	radians/s	radians/s

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