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Zhongchao Tan

Air Pollution and Greenhouse Gases

From Basic Concepts to Engineering Applications for Air Emission Control

Springer

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Preface

Air emissions include air pollution emissions and greenhouse gas emissions. Effective air emission control requires multidisciplinary expertise in engineering, education, physics, chemistry, mathematics, medical science, psychology, agriculture, architecture, business management, economics, and politics. It is a difficult task for the author(s) of any single book to address all aspects of air emissions. The focus of this book is on engineering science and technology, upon which effective air emission control program must be built. It does not prescribe social, economic, and political factors that lie outside the scope of this book.

This book aims at senior undergraduate and graduate students with educational backgrounds in mechanical, chemical, and/or environmental engineering. It can also be used by professionals with similar training background. It focuses on the basic concepts and engineering applications of technologies for the control of air emissions resulted from fossil fuel combustion.

This book is divided into three parts. The general basic concepts introduced in Part I are necessary to the understanding of air emission engineering topics in Parts II and III. Part II presents the engineering applications of the principles introduced in Part I. Part III covers some emerging topics related to air emission engineering and they include carbon capture and storage, nanoaerosol, indoor air quality.

Following a brief introduction to air emission in Chap. 1, Chaps. 2–4 present the general basic properties of gases and aerosol particles. They are necessary to understand the formation and behavior of air emissions. Chapters 5 and 6 present basic principles for the separation of unwanted gases and particulates from the contaminated air. These are the principles for the related engineering applications in Parts II and III such as syngas cleaning, carbon capture, and flue gas cleaning.

Part II of the book introduces the strategies for precombustion (Chaps. 7 and 8), in-combustion (Chap. 9) and postcombustion (Chap. 10) air emission control, step by step, from a process point of view. While air dispersion model (Chap. 11) is a powerful tool for air quality assessment and impact prediction, air dispersion itself is also a measure for air emission control by dilution.

Part III includes special topics related to the scope of this book, but they do not fit into the process introduced above. Chapter 12 is devoted to carbon sequestration and storage, which are of increasing interest to the society. Although debates are still ongoing, it is time to summarize the techniques that have been developed for CO_2 capture and storage. There may be some overlapping between this chapter and the other parts of this book. Chapter 13 presents an emerging topic of air pollution, nanosized air pollution. Nanomaterials are now widely used in many industries, for example, improved combustion efficiency, environmental protection, health, and solar panel fabrication. The unique properties of nanoaerosol and its implications on monitoring and filtration technologies are covered. Indoor air quality is introduced in Chap. 14. Indoor air quality is related extensively to air pollution. The sources of indoor air pollutants are different from their outdoor counterparts, as are their control techniques. The last chapter is about air quality and air emission monitoring techniques. They are commonly needed in industrial practices, government standard enforcement, and research and development in a laboratory setting.

The seed from which this book has grown was the engineering lecture notes that I have developed over the last 10 years. More teaching materials are available at this link: http://tan.uwaterloo.ca/book.html. They include PowerPoint presentations, extra assignment problems, and the solutions to the practice problems. They will be updated without notice.

Many people have helped me in writing this book, and my sincere appreciation goes to Dr. Dongqing Li (University of Waterloo), Dr. Mark Rood (University of Illinois at Urbana-Champaign), Raheleh Givehchi, Jing Min, Ishpinder Kailey, and all the undergraduate and graduate students who have commented on the manuscripts.

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Acronyms

AC	Activated Carbon
ACGIH	American Conference of Governmental and Industrial Hygienists
AFBC	Atmospheric Fluidized Bed Combustor
AFT	Adiabatic Flame Temperature
AQI	Air Quality Index
ASHRAE	American Society of Heating, Ventilating, and Air-conditioning Engineering
ASTM	American Society for Testing and Materials
B20	A mixture of 20 % of biodiesel with 80 % of petroleum diesel
BDC	Bottom Dead Center
BRI	Building Related Illness
CB_1	Coal Bug 1
CCS	Carbon Capture and Storage
CEM	Continuous Emission Monitoring
CFBC	Circulating Fluidized Bed Combustor
CLC	Chemical Looping Combustion
CLOU	Chemical Looping Combustion with Oxygen Uncoupling
CNT	Carbon Nanotube
CPC	Condensation Particle Counter
CRC	Chemical Rubber Company
CRT	Continuously Regenerating Trap
DI	Direct Injection
DMA	Differential Mobility Analyzer
DMT	Derjaguin, Muller, and Toporov
EDX	Energy-Dispersive X-ray Spectroscopy
EGR	Exhaust Gas Recirculation
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
ESP	Electrostatic Precipitator/Precipitation

EU	European Union
FBC	Fluidized Bed Combustion
FGR	Flue Gas Recirculation
FGD	Flue Gas Desulfurization
FSI	Furnace Sorbent Injection
GHG	Greenhouse Gas
HAP	Hazardous Air Pollutant
HC	Hydrocarbon
HFCs	Hydro Fluorocarbons
HHV	Higher Heating Value
HTC	Hydrothermal Conversion
HVAC	Heating, Ventilating, and Air Conditioning
IAQ	Indoor Air Quality
IDI	Indirect Injection Engine
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IL	Ionic Liquid
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IUPAC	International Union of Pure and Applied Chemistry
JKR	Johnson, Kendall, and Roberts
LCA	Life Cycle Analysis
LFL	Lower Flammable Limit
LHS	Left-Hand Side
LHV	Lower Heating Value
LIFAC	Limestone Injection into the Furnace and Activation of Calcium Oxide
LLB	Lurgi Lentjes Bischoff
MOF	Metal–Organic Framework
NAAQS	National Ambient Air Quality Standard
NGCC	Natural Gas Fired Combined Cycles
NIOSH	National Institute for Occupational Safety and Health
NREL	National Renewable Energy Laboratory
OSHA	Occupational Safety and Health Agency
PAH	Polycyclic Aromatic Hydrocarbon
PBL	Planetary Boundary Layer
PFBC	Pressurized Fluidized Bed Combustor
PFC	Perfluorinated Compound
PM	Particulate Matter
$PM_{2.5}$	Mass of particulate matter with particle diameters smaller than 2.5 μm
PM_{10}	Mass of particulate matter with particle diameters smaller than 10 μm
PM_x	Mass of particulate matter with particle diameters smaller than x μm
PSA	Pressure Swing Adsorption
PZ	Piperazine

R&D	Research and Development
RHS	Right-Hand Side
SBS	Sick Building Syndrome
SCR	Selective Catalytic Reduction
SEM	Scanning Electron Microscopy
SMPS	Scanning Mobility Particle Sizer
SNCR	Selective Non-Catalytic Reduction
Syngas	Synthesis Gas
TCC	Thermochemical Conversion
TDC	Top Dead Center
TEM	Transmission Electron Microscope
TGA	Thermo Gravimetric Analysis
THP	Total Heat Production
TLV	Threshold Limit Value
TLV-C	Threshold Limit Value-Ceiling
TLV-STEL	Short-Term Exposure Limit Threshold Limit Value
TLV-TWA	Time-Weighted Average Threshold Limit Value
TRS	Total Reduced Sulfur
UFL	Upper Flammable Limit
UN	The United Nations
US DOE	The United States Department of Energy
US EPA	The United States Environmental Protection Agency
USA	The United States of America
UV	Ultraviolet
VOC	Volatile Organic Compound
WGS	Water–Gas Shift
WHO	The World Health Organization
WWII	The Second World War
XRD	X-Ray Diffraction

Nomenclature

a	Packing material property (m^2/m^3)
a	Contact radius between particle and another surface (m)
A	Area (m^2)
A	Rate coefficient for reaction rate constant (Depends)
A_c	Cross-sectional area (m^2)
A_s	Filter porosity parameter (–)
A/F	Air fuel ratio in combustion (–)
b	Depth of the ESP plates (m)
B	Rate coefficients for reaction rate constant (Depends)
c_x	Molecular speed along x-direction (m/s)
c_y	Molecular speed along y-direction (m/s)
c_z	Molecular speed along z-direction (m/s)
c_{rms}	Root mean square speed (m/s)
$c_{p,a}$	Air heating capacity (J K/kg)
$\vec{c}$	A gas molecule velocity vector (m/s)
$\bar{c}$	Mean molecular speed (m/s)
$\vec{c}_{A/B}$	Average relative velocity (m/s)
$\bar{c}_i$	Mean thermal speed of the ions (m/s)
c_p	Specific heat of the fuel (kJ/pg)
C	Concentration of gas or air pollutant (kg/m^3)
C_e	Air pollutant concentration in air exiting the room (kg/m^3)
C_c	Cunningham correction factor (–)
C_D	Drag coefficient (–)
C_i	Concentration of the pollutant in entering the box in a box model (kg/m^3)
$C_{i\infty}$	Steady state air pollutant concentration when $t \rightarrow \infty$ (kg/m^3)
C_N	Normalized air pollutant concentration (kg/m^3)
C_N	Number of molecules per unit volume of the gas ($\#/m^3$)
C_o	Real concentration in the air stream (kg/m^3)
C_s	Air pollutant concentration in supply air (kg/m^3)
C_s	Mass of adsorbate per mass of adsorbent (kg/kg)

C_s	Sampled concentration (kg/m^3)
C_{ss}	The steady state concentration (kg/m^3)
C_{std}	Concentration corrected to 12 % CO_2 in the stack gas (kg/m^3)
C_x	Exit concentration in adsorption (kg/m^3)
C_u	A coefficient (–)
$C_{\Delta P}$	Pressure drop coefficient (–)
d	Diameter (m)
d_a	Aerodynamic particle diameter (m)
d_{bed}	Body diameter of granular filter bed (m)
d_c	Collision diameter (m)
d_c	Characteristic dimension (m)
d_e	Equivalent volume diameter (m)
d_f	Aerodynamic focusing orifice diameter (m)
d_f	Fiber diameter (m)
d_p^m	Maximum diameter of the focused particles (m)
d_p	Particle diameter (m)
d_G	Diameter of the granules (m)
d_{50}	Cut size, particle size for which the separation efficiency is 50 % (m)
D	Cyclone body diameter (m)
D	Diameter of the tube (m)
D	Characteristic length in Re (m)
D	The diffusivity or diffusion coefficient of gas in air (m^2/s)
D_e	Diameter of gas exit of a cyclone (m)
D_p	Diffusivity of the particles in the gas (m^2/s)
e	Coefficient of restitution (–)
e	Enhanced absorption factor (–)
e_k	Kinetic energy for one mole of an ideal gas (–)
E	Electric field intensity (V/m)
E_{ad}	Adhesion energy (J)
E_A	Activation energy (J/mol)
f	An empirical fitting factor (–)
f	Correction factor to the plume rise due to stack downwash (–)
f_D	Dimensionless Darcy friction factor (–)
f_v	Vapor mass fraction at the droplet surface (–)
F	Force (N)
F_B	Buoyancy flux (m^4/s^3)
F_C	Centrifugal force (N)
F_D	Drag force (N)
F_M	Momentum flux (m^4/s^2)
Fr	Froude number (–)
g	Gravitational acceleration, 9.81 (m/s^2)
G	Mole flow rate of the gas mixture (mol/s)
$\bar{G}$	Mole flow rate of the solute-free carrier gas (mol/s)
Gr	Gravity number (–)

h	Height or length of a packed bed filled with granules (m)
h	Sensible heat of air (kJ/kg of dry air)
h_e	Total enthalpy of the air exiting the room (J)
h_{fg}	Latent heat of vaporization of water (J/mol)
h_{fg}	Latent heat of vaporization of the liquid fuel (J/mol)
$h^o_{f,i}$	Heat of formation of substance i (J/mol)
h_s	Total enthalpy of the supply air (J)
$h(T)$	Molar enthalpy of a component at temperature T (J/mol)
H	Cyclone height of inlet (m)
H	Distance between two plates of ESP (m)
H	Hamaker constant (J)
H	Henry's law constant (Depends)
H	Length/height of the column (m)
H	Plume center height (m)
H	Total enthalpy (J)
H_c	Critical height of a settling chamber (m)
H_{ij}	Hamaker constant (J)
H_B	Height of the building (m)
HHV	Higher Heating Value (J/mol)
HTU	Height of transfer unit (–)
I	Electric current (A)
j_x	Number of molecule colliding with the wall per unit area per unit time (1/s m^2)
J	Flux of mass flow per unit area (kg/s m^2)
J_x	Collision per unit time per unit area (1/m^2)
k	Boltzmann constant, 1.3807×10^{-23} (J/K)
k	Chemical reaction coefficient corresponding to y_{ss} (mol/s)
k	Karman constant = 0.4 (–)
k	Permeability of the porous medium (m^2)
k	Permeability of a filter dust cake (m^2)
k	Rate constant of the reaction (Depends)
k	Thermal conductivity of the liquid droplet at the surface (W/(m K))
k_{AmH}	Reaction rate constant of CO_2 and the amine (m^3/mol s)
k_b	Rate constant for the backward/reverse reaction (Depends)
k_f	Rate constant for the forward reaction (Depends)
k'_g	Amine liquid film mass transfer coefficient (m/s)
k_P	Mechanical constant of the particle (–)
k_y	Gas phase mass transfer coefficient (mol/m^2 s)
k_x	Liquid phase mass transfer coefficient (mol/m^2 s)
k_1	Mass transfer coefficient (depends)
k_2	Mass transfer coefficient (depends)
K_f	Mechanical constant of the particle filter materials (–)
Kn	Knudsen number (–)
K_C	Concentration based chemical equilibrium constant (Depends)

K_E Force constant of proportionality, 9×10^9 (Nm^2/C^2)
K_P Partial pressure based equilibrium constant (Depends)
K_{P0} Partial pressure based equilibrium constant under a reference condition (Depends)
K Aerosol coagulation coefficient (–)
K_x Mass transfer rate coefficient in adsorption (1/s)
K_x Overall mass transfer coefficient for the liquid phase (mol/m^2 s)
K_y Overall mass transfer coefficient for the gas phase (mol/m^2 s)
L Length of the ESP plates (m)
L Mole flow rate of the liquid (mol/s)
L Obukhov Length (m)
L_B Cyclone body length (m)
L_C Cyclone cone length (m)
$\bar{L}$ Mole flow rate of the solute fee liquid (mol/s)
LHV Lower Heating Value (J/mol)
m Mass of a molecule (kg)
$\dot{m}$ Air emission rate by mass (kg/s)
$\dot{m}$ Mass flow rate of fluid (kg/s)
m_i^0 Molality (mol/kg)
m_l Mass of the fuel droplet (kg)
m_w Mass of water vapor in given air volume (kg)
$m_{w,s}$ Mass of water vapor required to saturate (kg)
$\dot{m}_v$ Liquid fuel droplet vaporization rate (kg/s)
M Molar weight (kg/kmol)
M_{eq} Equilibrium concentration in adsorption (kg/kg)
$M_{\max}$ Maximum loading potential of adsorbate that can be loaded to per mass of adsorbent (kg/kg)
M_x Flux of momentum along x-direction (1/s m^2)
n Mole amount of gases (mol, kmol)
n Number of ions (–)
n Number of molecules (–)
n Particle number concentration (1/m^3)
n' Mole transfer of pollutant (mol/m^2 s)
n_c Number of molecule colliding with the wall (–)
N Number of aerosol particles (–)
N Cumulative number of particles deposited per unit area of surface (1/m^2)
N_e Number of turns the gas flow makes before turning upward in a cyclone
N_{i0} Ion concentration in the charging zone (1/m^3)
N_{vdw} Van der Waals number (J m^3/mol^2)
N_A Avogadro constant, 6.022×0^{23} (1/mol)
NTU Number of transfer unit (–)
p_{sat} Saturation vapor partial pressure at the actual dry bulb temperature (Pa)
p_w Vapor partial pressure (Pa)

$p(x)$	Probability function (–)
P	Gas pressure (Pa)
P	Potential energy (J)
P_i	Partial pressure of gas i in the gas phase above the liquid (Pa)
P_p	Penetration efficiency of particles (–)
$P^n_{o_2}$	Partial pressure of the oxidizer (Pa)
P^0_v	The original vapor pressure (Pa)
Pe	Peclet number (–)
Pe_m	Modified Peclet number (–)
q	Charge carried by particle (C)
$\dot{q}$	Total sensible heat transfer rate (J)
Q	Heat added to the system (J)
Q	Volumetric gas flow rate (m^3/s)
Q_e	Volumetric flow rate of exhaust air (m^3/s)
Q_e	Air exits in the room at a volumetric flow rate (m^3/s)
Q_i	Volumetric flow rate of internal air cleaning (m^3/s)
Q_o	Volumetric flow rate of fresh air (m^3/s)
Q_r	Volumetric flow rate of recirculating air (m^3/s)
Q_s	Intake (supply) fresh air volumetric flow rate (m^3/s)
Q_{sh}	Sheath air flow rate (m^3/s)
r	Radial position (m)
r_A	Reaction rate (mol/m^3 s)
r_s	Radius of a droplet (m)
r_{s0}	Initial droplet diameter (m)
r_{EGR}	EGR percentage (–)
r^*	Dimensionless distance from the center of the fiber (–)
r_1	Inner radius of annular space (m)
r_2	Outer radius of annular space (m)
R	Interception parameter (m)
R	Universal ideal gas constant, 8.314 (J/mol K)
R	Overall resistance to mass transfer (m/s)
R_x	Liquid phase resistance to mass transfer (m/s)
R_y	Gas phase resistance to mass transfer (m/s)
R^*	Characteristic radius of two bodies in contact (m)
Re	Reynolds number (–)
Re_p	Particle Reynolds number (–)
Re_x	Boundary layer Reynolds number at x (–)
RH	Relative humidity (–)
S	Internal source rate with respect to the air pollutant (Depends)
S	Length of vortex finder of a cyclone (m)
$\dot{s}$	Pollutant production rate in the room (kg/s)
s_f	Length of the uniform single fiber (m)
S_f	Particle shape factor (–)
s_z	Atmosphere stability indicator (–)

Stk	Stokes number (–)
Stk_m	Modified Stokes number (–)
Stk^*	Critical Stokes number (–)
t_e	The life time of fuel droplet (s)
t_x	Breakthrough time of an adsorption column (s)
T	Temperature (K)
T_a	Adiabatic flame temperature (K)
T_0	Initial temperature (K)
T_0	Reference temperature (K)
T_s	Sutherland's constant (K)
T_s	Surface temperature of the fuel droplet (K)
T_v	Vaporization temperature for the liquid fuel (K)
THP	Total heat production of occupants (J/s)
TLV	Threshold limit value of the air pollutant (Depends)
u	Velocity (m/s)
u_g	Magnitude of the mean fluid velocity (m/s)
u_s	Vapor speed leaving the surface of the fuel droplet (m/s)
u_∞	Air speed of the free steam (m/s)
u_*	Friction speed (m/s)
u_{10}	Wind speed at 10 m above the ground (m/s)
$\bar{u}_g$	Mean gas speed (m/s)
u_θ	Transverse/tangential speed (m/s)
U	Gas velocity (m/s)
U_0	Air speed approaching the filter fiber (m/s)
U_0	Free air stream velocity (m/s)
U_s	Sampling velocity (m/s)
U_∞	Air velocity approaching the filter (not the fiber) (m/s)
v	Speed of the air parcel (m/s)
v	Gas specific volume (m^3/kg)
v	Velocity on the streamline (m/s)
v_f	Average air velocity in the focusing orifice exit plane (m/s)
v_r	Radial speed of the particle (m/s)
v_s	Stack emission speed (m/s)
v_{TS}	Terminal settling velocity (m/s)
v_0	Initial velocity of particle in the still air (m/s)
v_{cr}	Particle critical velocity (m/s)
$\bar{v}_{im}$	Mean impact velocity in thermal rebound (m/s)
v_{im}	Impact velocity in thermal rebound (m/s)
v_θ	Transverse/tangential speed (m/s)
V	Total reactor volume (m^3)
V	Volume of the indoor pace (m^3)
V	Volume of gas (m^3)
V	Volume of the air parcel (m^3)
V	Voltage of ESP (V)

V_{az} Adsorption wave propagation speed (m/s)
V_E Terminal precipitating velocity of ESP (m/s)
$\bar{V}$ Average voltage on the inner collector rod (V)
w Water vapor mass fraction in the air (kg vapor/kg air)
w Humidity ratio of air (–)
w Specific humidity of air (–)
w_e Moisture content of the air exiting the room (–)
w_s Moisture content of the supply air (–)
$\dot{w}$ Moisture production rate in the room (kg/s)
W Weight of the adsorbent packed (kg)
W Work done by the system on the surroundings (J)
x Mole ratio in the bulk liquid phase (–)
x_c Critical distance for maximum plume rise (m)
x_i The equilibrium concentration of gas i in the liquid phase (mol/m^3)
x_F Remaining mass fraction of the solid fuel (–)
x^* Hypothetical mole fraction corresponding to x in the bulk fluid (–)
X Mole ratio of pollutant to the corresponding liquid (–)
X^* Hypothetical or equilibrium mole ratio in gas (–)
y Mole fraction of the target gas at gas–liquid interface (–)
y_i Mole fraction at the interface in gas phase (–)
y_{ss} Mole fraction of the target gas in the bulk liquid at steady state (–)
y^* Hypothetical mole fraction corresponding to y in the bulk fluid (–)
Y Mole ratio of pollutant to the corresponding gas (–)
Y Hydrodynamic factor (–)
Y^* Composite Young's modulus (N/m^2)
Y^* Hypothetical or equilibrium mole ratio in gas (–)
z Elevation (m)
z_0 Surface roughness height (m)
Z_e Mobility of the ions (m^2/V s)
z_{mix} Mixing height in atmosphere (m)
Z_e Equilibrium distance between the particle and another surface (0.4 nm) (m)
Z_p Electrical mobility of a particle (m^2/V s)
Z_p^* Optimum electrical mobility of a particle (m^2/V s)
α Solidification of a filter (–)
δ Boundary layer thickness (m)
δ Width of the adsorption wave (m)
δ_{AB} Jump distance in analyzing the aerosol coagulation (m)
Δh Plume rise (m)
Δh_m Maximum plume rise (m)
ΔH_R Enthalpy of reaction (J/mol)
Δt Time difference (s)
ΔP Pressure drop across the filter (a positive number) (Pa)
ΔU Internal energy in the system (J)
Δx Thickness of the porous media (m)

$\Delta\gamma$	Specific adhesion energy (J/m^2)
ε_r	Relative permittivity of the fiber (–)
ε_r	Relative permittivity or dielectric constant of the particle with respect to vacuum (–)
ε_0	Permittivity of a vacuum, 8.854×10^{-12} (C/V m)
η_{ad}	Particle adhesion efficiency (–)
η_D	Single fiber efficiency by diffusion (–)
η_{ip}	Single fiber efficiency by impaction (–)
η_{it}	Single fiber filtration by interception (–)
η_s	Sampling efficiency (–)
η_{sG}	Single granule efficiency (–)
η_{sf}	Total efficiency of a single fiber (–)
η_{ts}	Particle transport efficiency (–)
η_p	Separation efficiency for particles (–)
η_x	Breakthrough efficiency in adsorption (–)
θ	Angle (rad)
λ	Mean free path of gas (m)
μ	Kinetic (Dynamic) viscosity (Pa s, N s/m^2)
ρ	Density (kg/m^3)
ρ_a	Density of the surrounding air (kg/m^3)
ρ_b	Bulk density of the adsorbent (kg/m^3)
ρ_0	Ground level air density (kg/m^3)
ρ_p	Density of the air parcel (kg/m^3)
ρ_p	Particle density (kg/m^3)
ρ_r	Reaction rate ratio (–)
σ_g	Geometric standard deviation (–)
σ_y	Dispersion coefficient in the transverse (y) direction (m)
σ_z	Dispersion coefficient in the vertical (z) direction (m)
τ	Characteristic time for aerodynamic particle settling (s)
τ	Half-value time in aerosol coagulation (s)
τ	Shear stress (N/m^2)
τ_0	The ground level (surface) shear stress (m)
Φ	Equivalence ratio in combustion (–)
Φ	Latitude where the air is of concern (–)
$\emptyset(u)$	Cumulative probability function (–)
Ω	Angular speed of the earth, 7.25×10^{-5} rad/s
$[i]$	Mole concentration (mol/m^3)