AIR POLLUTION
Its Origin and Control

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Preface

This text was developed over the past four years from notes written for an introductory air pollution course for engineers and scientists. The students, primarily from mechanical, civil, chemical, and environmental engineering, who used these notes had widely varying technical backgrounds, but they all had knowledge of a common set of basic physical principles. We sought to develop every major topic from these first principles. Hence the material should be suitable for a variety of engineers who wish to gain an introduction to the field of air pollution and its control.

An understanding of the fundamentals of thermodynamics is assumed, including the concepts of chemical equilibrium for chemically reactive ideal-gas mixtures typically presented in a second course in engineering thermodynamics. A grasp of basic concepts in chemical kinetics is important to understand fully the origin and persistence of numerous pollutants. Since this subject matter is not commonly taught in many undergraduate engineering programs, we present the required principles in a separate section of this text. Their use is then illustrated in subsequent sections for specific areas of interest. We also review some of the basic principles of mass transfer before presenting the control methods involving absorption.

Although we can anticipate the gradual changeover to S. I. units, a massive proportion of the data available in the literature is in units peculiar to a particular area of interest. Hence a student of air pollution control must be conversant with—and tolerant of—a large set of diverse engineering units. To minimize this problem, Appendix B contains conversion tables for a number of units commonly used in the field. In the text's problem sections, we use S. I. units wherever feasible.

The text presents information on four broad areas of interest in the air pollution field. First, the effects of pollutants on health and welfare are described briefly; second, federal laws and regulations that have been promulgated in an attempt to achieve reasonable ambient air quality are summarized; and third, a model for atmospheric dispersion of pollutants, including meteorological effects on dispersion patterns, is developed. The fourth area concerns the general and specific approaches to the control of emissions from sources—small- and large-scale, mobile and stationary, combustion and noncombustion—and is covered in detail. The physical and chemical mechanisms responsible for the effectiveness of a given control device are presented in some depth as are the physical configuration and important macroscopic parameters associated with each device. In addition, we comment briefly on the instrumentation required for the accurate and reliable monitoring of pollutants in gas streams and in the environment. The subject of instrumentation has not been covered in any depth, since any realistic coverage would require an inordinate amount of space. Innumerable articles and books on instrumentation are available in the current literature. Although we present some economic data, especially for comparative purposes, we do not attempt a comprehensive list of cost factors because construction and operating costs are subject to considerable variation. Cost data are readily available from fabricators of pollution control equipment. A list of references is included at the end of each chapter, as well as discussion questions and problems.

It is not possible for any air pollution control text of moderate length to present complete coverage of the field. The space devoted to any particular topic, and the omission of other topics, is mainly a matter of the author's choice. In addition, air pollution control is an active and creative field; new methods of control and measurement are constantly being introduced. New or modified laws and regulations are continually being promulgated, albeit at a slower pace than the initial flurry of legislative activity in the late 1960s and early 1970s. Only regular perusal of the current literature will enable the reader to keep abreast of the development in this rapidly changing field.

Symbols

LETTER SYMBOLS

A	Cross-sectional area
a	Absorption coefficient for light
	Acceleration
B	Magnetic field intensity
C	Concentration
C_D	Drag coefficient
Coh	Coefficient of haze
c_p	Specific heat at constant pressure
D	Dielectric constant
	Mass diffusivity
D_L	Liquid-phase diffusion coefficient
d	Distance
	Stack diameter

E	Activation energy
	Electric field strength
e	Electric charge
F	Dimensional parameter in plume-rise evaluation
	Force
G	Gas flow rate
g	Gravitational acceleration
g_c	Gravitational constant
H	Effective stack height
	Height of gravity settling chamber
H_t	Height of a transfer unit
h	Actual stack height
	Enthalpy
Δh	Plume rise
I	Light intensity
K	Dust permeability
	Eddy diffusion coefficient
	Mass transfer coefficient
	Scattering ratio
K_c	Cunningham correction factor
K_p	Ideal-gas equilibrium constant
k	Boltzmann's constant
	Mass transfer coefficient
	Rate constant
	Specific heat ratio, c_p/c_v
L	Length
	Liquid flow rate
L_V	Limit of visibility
M	Molar mass (molecular weight)
m	Mass
	Refractive index
MB	million Btu
N	Mass transfer per unit time and unit area
	Number of particles per unit volume
N_e	Number of effective turns in a cyclone
N_I	Impaction number
N_t	Number of transfer units
n	Exponent in wind velocity profile
P	Pressure
	Odor intensity
p	Pressure
Q	Mass emission rate, mass per unit time
	Volume flow rate

Q_{h}	Heat emission rate, energy per unit time
q	Electric charge
	Emission source strength per unit length
	Quantity of heat transfer
R	Ideal-gas constant
	Radius
Re	Reynolds number, $DV\mu/\rho$
r	Radius (of particle)
S	Filter drag
	Odor concentration
	Separation distance
s	Scattering coefficient for light
T	Temperature
T_{frac}	Fractional light transmission
t	Time
u	Internal energy
	Wind speed
V	Velocity
	Volume
	Voltage
v	Specific volume
W	Mass of adsorbent
	Width
w	Drift velocity
	Work interaction
X	Liquid-phase mole ratio
x	Distance or coordinate
	Mole fraction
x_s	Stopping distance
Y	Gas-phase mole ratio
y	Distance or direction
	Gas-phase mole fraction
z	Distance or direction

GREEK SYMBOLS

η	Efficiency
θ	Potential temperature
Γ	Adiabatic lapse rate
λ	Wavelength

μ	Microns (micrometers)
	Parameter in Gaussian distribution
	Viscosity
ρ	Density
ρ_e	Electrical resistivity
σ	Extinction coefficient
	Standard deviation
ϕ	Angle
	Equivalence ratio
v	Ion velocity

SUBSCRIPTS

a	Atmosphere
C	Carrier gas
G	Gas phase
i	ith species
L	Liquid phase
m	Molar value
OG	Over-all gas-phase value
OL	Over-all liquid-phase value
S	Solvent
s	Stack
x	Based on mole fraction in liquid phase
y	Based on mole fraction in gas phase

Contents

8

CONTROL OF OXIDES OF NITROGEN FROM STATIONARY SOURCES 357

9

ATMOSPHERIC PHOTOCHEMICAL REACTIONS 395

10

MOBILE SOURCES 417

1

Effects and Sources of Air Pollutants

1-1 INTRODUCTION

Air pollution is woven throughout the fabric of our modern life. A by-product of the manner in which we build our cities, air pollution is waste remaining from the ways we produce our goods, transport ourselves and our goods, and generate the energy to heat and light the places where we live, play, and work. The major cause of all air pollution is combustion, and combustion is essential to man. When perfect or theoretical combustion occurs, the hydrogen and carbon in the fuel combine with oxygen from the air to produce heat, light, carbon dioxide, and water vapor. However, impurities in the fuel, poor fuel-to-air ratio, or too high or too low combustion temperatures cause the formation of such side products as carbon monoxide, sulfur oxides, nitrogen oxides, fly ash, and unburned hydrocarbons—all air pollutants.

Air pollution is not a recent phenomenon. King Edward I of England tried to clear the smoky sky over London in 1272 by banning the use of "sea coal." The British Parliament ordered the torturing and hanging of a man who sold and burned the outlawed coal. Under Richard III (1377–1399) and later under Henry V (1413–1422), England took steps to regulate and restrict the use of coal [1]. One of the earliest recorded publications dealing with air pollution is a pamphlet published in 1661 by royal command of Charles II: "Fumifugium; or the Inconvenience of the Air and Smoke of London Dissipated; together with Some Remedies Humbly Proposed," written by John Evelyn, one of the founding members of the Royal Society [1]. The use of coal in the generation of energy was a major factor in the Industrial Revolution, which formed the basis of our current technological society. Unfortunately, intimately associated with the benefits of our technological society is the fouling and degrading of our environment. One of the earliest legal attempts to control air pollution in the United States appears to be an 1895 ordinance making illegal the "showing of visible vapor" as exhaust from steam automobiles.

Such natural processes as forest fires, decaying vegetation, dust storms, and volcanic eruptions have always contaminated the air. Although the total global production of many gases and particulate matter recognized as pollutants is much greater from natural sources than from man-made sources, global distribution and dispersion of those pollutants result in low average concentrations. By precipitation, oxidation, and absorption into the oceans and the soil, the atmosphere can cleanse itself of all known pollutants given sufficient time [2, 3]. On the other hand, man-generated pollutants are usually concentrated in small geographic regions; hence most air pollution is truly man-made. In the United States alone, over 200 million tons of gaseous, solid, and liquid waste products are discharged annually into the atmosphere. Currently the rate at which pollutants are discharged into the atmosphere in highly populated regions at time exceeds the cleansing rate of the atmosphere.

1-2 AIR POLLUTION EPISODES

Although limited air pollution was experienced as early as 1272, it has become a major problem only in relatively recent years, considering man's total history. In December, 1930, a heavily industrialized section of the Meuse Valley, in Belgium, experienced a severe 3-day fog during which hundreds of people became ill and 60 died—more than 10 times the normal number. Shortly afterward, during a thick 9-day fog in January, 1931, 592 people in the Manchester and Salford area of England died—again a large jump in the death rate. In 1948, in Donora, Pennsylvania, a small mill town dominated by steel and chemical plants, a 4-day fog made almost half of the 14,000 inhabitants sick. Twenty persons died. Ten years later, Donora residents who had been acutely ill during that episode were found to have a higher rate of sickness and to die at an earlier age than the average for all the townspeople. During a fog in London as far back as 1873, 268 unexpected deaths from bronchitis were reported. It was not until a great fog blanketed London in 1952 that the sinister potential of air pollution became fully apparent. That fog lasted from December 5 to December 8, and 10 days later it was learned that the total number of deaths in Greater London during that period exceeded the average by 4000. The statistics indicated that almost all those who died unexpectedly had records of bronchitis, emphysema, or heart trouble, and that people in the last category were most vulnerable. Again in January, 1956, 1000 extra deaths in London were blamed on an extended fog. In that year, Parliament passed a Clean Air Act and Britain embarked on a program to reduce the burning of soft coal [4]. The smog conditions of Los Angeles, New York City, Chicago, and other large cities of the United States are widely publicized in today's press.

The misuse of air resources in the USSR is not very different from that in this country. Despite the fact that Russia's current yearly production of cars is one-tenth that of the United States, most Soviet cities experience varying degrees of air pollution. Cities situated in valleys or hilly regions are especially likely to experience dangerous levels of air pollution. In the hilly cities of Armenia, for example, the established health standards for carbon monoxide are often exceeded. Similarly, Magnitogorsk, Alma Ato, and Chelyabinsk, with their metallurgical industries, are frequently covered with a layer of dark blue haze. Like Los Angeles, Tbilisi, the capital of the Republic of Georgia, has smog almost 6 months of the year. Leningrad has 40 percent fewer clear daylight hours than the nearby town of Pavlovsk [5].

1-3 GENERAL NATURE OF AIR POLLUTION PROBLEMS

Only a finite amount of air, land, and water resources exist, and as population increases, the portion available for each person decreases. From the beginning of time until 1900, the population of the world increased to 1.7 billion. By 1974 world population had reached 3.9 billion, and the awesome figure of 7 billion is estimated by the year 2000. The population of the United States has followed a similar trend. In addition, technological advances in the field of agriculture have greatly reduced the number of jobs in rural areas. As in other developed countries, today two-thirds of the population lives in urban areas comprising about 1 percent