AIR POLLUTION

Its Origin and Control

Kenneth Wark
and Cecil F. Warner

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Second Edition

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Preface

The first edition of this text has been modified in three broad areas. First, new material has been added in several chapters in order to improve upon the coverage of material. For example, a more thorough discussion of particulate distributions is presented, in conjunction with the material on fractional and overall collection efficiencies. A mathematical analysis of the adsorption wave and its transient behavior also has been included. Secondly, old material has been updated, or removed if no longer appropriate. A major example of this is the complete rewriting of the section on flue gas desulfurization. The chapter on mobile sources has also undergone revision that reflects changes in technology or legislation. Lastly, a considerable number of new problems have been added (and a few old ones removed). This is in keeping with the authors' general philosophy that the reader of this text should be exposed to both the quantitative and qualitative aspects of air pollution control. The data for these new problems are presented in both conventional English units and SI units. SI units are emphasized to a somewhat greater extent than in the first edition. However, a student of air pollution control must be conversant with 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.

It is our intent that the material 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 some knowledge of chemical equilibrium for ideal-gas mixtures. The required principles of chemical kinetics, important to understand more fully the origin and persistence of numerous pollutants, is presented in the text. A review of some of the basic principles of mass transfer is also given in the text, before presenting the control methods involving absorption.

The new edition continues to present information on four broad areas of interest in the air pollution field: (1) the effects of pollutants on health and welfare, (2) the federal laws and regulations that have been promulgated in an attempt to achieve reasonable ambient air quality, (3) the modeling of atmospheric dispersion of pollutants, and (4) the general and specific approaches to the control of emissions—small- and large-scale, mobile and stationary, combustion and noncombustion. The mechanisms responsible for the effectiveness of a given control device are discussed in some depth. The instrumentation required for the accurate and reliable monitoring of pollutants is covered briefly, since innumerable articles and books are available on the subject in the current literature. Some economic data are presented for comparative purposes. However, inflation has a large effect on construction and operating costs, so a comprehensive list of cost factors is not included.

Similar to the first edition, no attempt has been made to present a complete coverage of the air pollution control field. The space devoted to any particular topic, and the omission of other topics, is mainly a matter of the authors' choice. New methods of control and measurement are constantly being introduced; new or modified laws and regulations are continually being promulgated. Only regular perusal of the current literature will enable one to keep abreast of the developments in the area of air pollution control processes.

Kenneth Wark
Cecil F. Warner

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
	Number of particles under given size
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
	Number of particles per differential size
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
	Particulate resistance
Re	Reynolds number, $DV\rho/\mu$
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
	Logarithm of particle diameter
	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
μm	Microns (micrometers)
μ	Parameter in Gaussian distribution
	Viscosity
ρ	Density
ρ_e	Electrical resistivity
σ	Extinction coefficient
	Standard deviation
ϕ	Angle
	Equivalence ratio
ν	Ion velocity

SUBSCRIPTS

a	Atmosphere
C	Carrier gas
G	Gas phase
i	ith species
L	Liquid phase
MM	Mass median
m	Molar value
NM	Number median
OG	Overall gas-phase value
OL	Overall liquid-phase value
S	Solvent
s	Stack
x	Based on mole fraction in liquid phase
y	Based on mole fraction in gas phase

Air Pollution

Contents

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 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 duing 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 of the land. Suburban growth and superhighways have made it possible for more people to travel greater distances and thus to converge faster on our cities. Hence an increasing population combined with a high standard of living has led to a drastically intensified output and concentration of air pollutants in localized areas.

COUNTRY	GROSS NATIONAL PRODUCT ($/CAPITA)	COMMERCIAL ENERGY CONSUMPTION (MILLION Btu/CAPITA)	GNP / ENERGY
India	50	5	10
Chile	450	20	22
Japan	600	30	20
USSR	900	70	13
West Germany	1450	85	17
United Kingdom	1500	117	13
Canada	1900	130	15
United States	2850	180	16

During a recent time period in which the population of the United States doubled, there was an eightfold increase in the gross national product (GNP) and an increase in the production of electrical energy by a factor of 13. For developed or developing countries, there appears to be a close relationship between the gross national product per capita (economic level) and energy consumption per capita. This is illustrated by data for selected countries taken from Cook's study of the flow of energy in an industrialized society [6]. All values in the table (see page 3) are approximate.

These data indicate that the quantity of goods and services enjoyed by a citizen is closely related to the quantity of energy consumed (directly or indirectly) by that citizen. In other words, the availability and use of energy is a requisite for a high standard of living. It is striking to translate the American experience into global terms. An increase in energy demand per capita in the developing countries, similar to that experienced in West Germany and the United States, in combination with the increase in global population could result in uncontrolled emissions of air pollutants in catastrophic proportions.

In the past, industry, agriculture, and individual polluters have found it more economical to discharge waste products into the atmosphere than to exercise waste control. In general the organization or activity causing the pollution did not suffer the consequences of the pollution; likewise, those who benefited from a reduction in air pollution resulting from the installation of control equipment did not directly bear the cost of the equipment. In recent years, as the public has become increasingly concerned with environmental problems, air has come to be regarded as a resource within the public domain. Hence air pollution is considered a public problem, a concern not only of those who discharge the pollution, but also of those who may suffer as a result. Thus the laws in some countries now permit an individual or group of private individuals to sue directly an organization or company which is polluting that particular part of the public domain.

The rational control of air pollution rests on four basic assumptions [7].

1. *Air is in the public domain.* Such an assumption is necessary if air pollution is to be treated as a public problem, of concern not only to those who discharge the pollution but also to those who may suffer as a result.

2. *Air pollution is an inevitable concomitant of modern life.* There is a conflict between man's economic and biologic concerns; in the past, this conflict was recognized only after air pollution disasters. We need a systematic development of policies and programs to conserve the atmosphere for its most essential biological function.

3. *Scientific knowledge can be applied to the shaping of public policy.* Information about the sources and effects of air pollution is far from complete, and a great deal of work must be done to develop control devices and methods. Nevertheless, sufficient information is now available to make possible substantial reductions in air pollution levels. Man does not have to abandon either his technology or his life, but he must use his knowledge.