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AIR POLLUTION ITS ORIGIN AND CONTROL

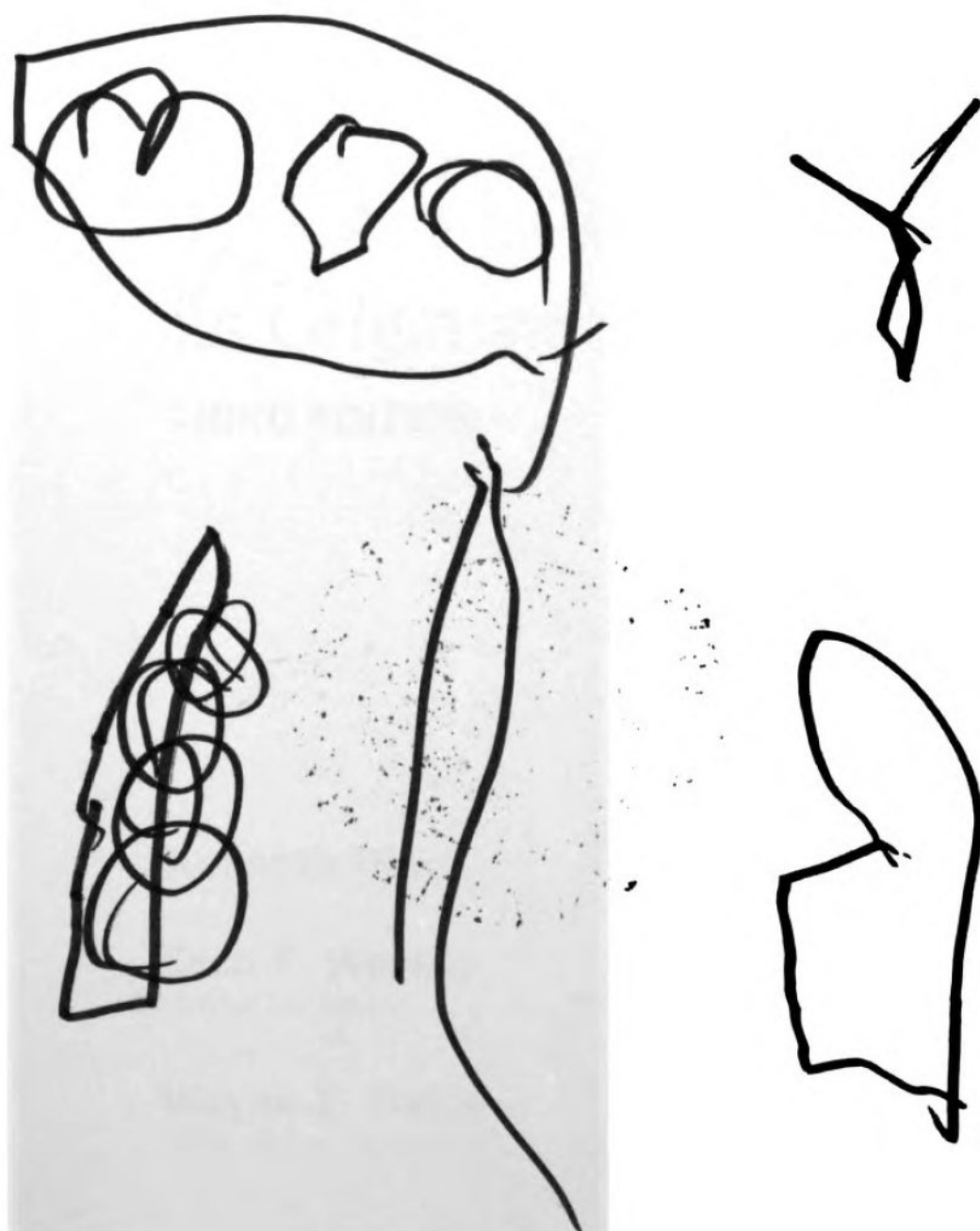
THIRD EDITION

KENNETH WARK - CECIL F. WARNER - WAYNE T. DAVIS

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Air Pollution

Its Origin and Control

THIRD EDITION

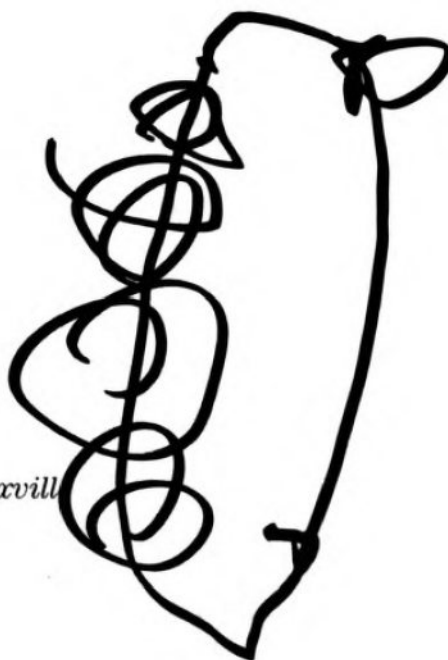
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Preface

The third edition of this text provides a much needed update to the second edition which was published prior to the promulgation of the Clean Air Amendments of 1990. This latest edition has been modified in four broad areas. First, new material has been added to bring the text up to date on the regulations. The Clean Air Act Amendments of 1990 placed increased emphasis on requirements associated with nonattainment areas, placed more emphasis on control of emissions from fossil fuel-fired power plants and other combustion sources, and focused more effort on a large number of pollutants now regulated as hazardous air pollutants. These regulations are discussed in detail in this new edition.

Secondly, many of the ambient air quality and emission standards have become more stringent or more specific since the publication of the second edition and are now being revised on a more frequent basis. These latest standards are included in the text. Examples include emission standards for municipal waste combustors and medical and hazardous waste incinerators, all of which underwent changes during the writing of this edition during the last two years. Another example is the incorporation of particle size specific standards such as the PM_{10} standard and the $PM_{2.5}$ standard which address the mass of particles less than or equal to 10 and 2.5 micrometers, respectively. The chapters which cover combustion have been expanded to include more details on understanding combustion, combustion balances, incineration, and control of combustion processes. The chapter on mobile sources has been expanded to include the latest emission standards and the control technologies required to meet the standards.

Thirdly, new questions and problems have been added (and some older 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 quality management and air pollution control. The data for these problems are presented in both conventional English units and SI units. SI units are emphasized to a somewhat greater extent than in the second edition. However, a student in the air pollution field 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.

Lastly, this edition introduces the use of the Internet as a valuable source of additional supplemental information. Specific references have been included to direct the reader to many of the sources which are available on the World Wide Web, such as the U.S. EPA Technical Transfer Network Bulletin Board System



(TTNWeb). Dr. Wayne T. Davis, the new third author of the text, and primary contributor to this edition, has established a Web page which provides hot links to sources of information that are of particular value to the text. The authors encourage students to use the Web page and welcome comments or suggestions which might enhance the use of the text. The Web page can be accessed at <http://funnelweb.utcc.utk.edu/~wtdavis/>.

It is our intent that the text be suitable for a variety of engineers and scientists who wish to gain an introduction to the field of air pollution and its management and control. An understanding of the fundamentals of thermodynamics is assumed, including some knowledge of chemical equilibrium for ideal-gas mixtures. The principles of chemical kinetics required to understand more fully the origin and persistence of numerous pollutants are 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 laws and regulations that have been promulgated in an attempt to achieve and maintain acceptable ambient air quality, (3) the modeling of atmospheric dispersion of pollutants, and (4) the general and specific approaches to the control of particulate and gaseous emissions—small and large scale, mobile and stationary, combustion and noncombustion. The mechanisms responsible for the effectiveness of each control device are discussed in some depth.

As with previous editions, 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. In addition, no attempt has been made to present complete coverage of the air pollution control field. The space devoted to any particular topic and the omission of other topics are mainly choices of the authors after input from various reviewers and users of previous editions. New method 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 the reader to keep abreast of the developments in the areas of air quality management and air pollution control.

The authors express their sincere appreciation to the following faculty members at various universities who assisted in the review of various chapters of this latest edition. They include, in alphabetical order: Dr. Dan P. Chang (University of California, Davis), Dr. Harold M. Cota (California Polytechnical Institute at San Luis Obispo), Dr. Mackenzie L. Davis (Michigan State University), Dr. Timothy C. Keener (University of Cincinnati), Dr. Ashok Kumar (University of Toledo), Dr. Thomas J. Overcamp (Clemson University), Dr. George P. Partridge, Jr. (Pennsylvania State University at Harrisburg), and Dr. Mark J. Rood (University of Illinois at Champaign-Urbana).

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Symbols

Letter Symbols

A	Cross-sectional area
a	Acceleration
B	Magnetic field intensity
C	Concentration
C_D	Drag coefficient
c	Packing density
C_p	Specific heat at constant pressure
D	Dielectric constant
	Mass diffusivity
D_b	Adsorption bed depth
D_L	Liquid-phase diffusion coefficient
d	Distance
	Particle diameter
	Stack diameter
E	Activation energy
	Electric field strength
e	Electron charge
F	Force
	Packing factor
F_b	Buoyancy flux parameter in plume rise
F_m	Momentum flux parameter in plume rise
G	Adsorption capacity, volume of adsorbate/mass of adsorbent
	Gas flow rate
g	Gravitational acceleration
g_c	Gravitational constant
H	Effective stack height
	Height of gravity settling chamber
H_t	Height of transfer unit
h	Enthalpy
	Planck's constant
h_s	Actual stack height
h_s'	Stack height corrected for stack tip downwash
Δh	Plume rise
I	Light intensity
K	Eddy diffusion coefficient
	Mass transfer coefficient
	Scattering ratio
K_c	Dust permeability
K_C	Cunningham correction factor
K_p	Ideal-gas equilibrium constant
K_2	Dust resistance coefficient

k	Boltzmann's constant Mass transfer coefficient Rate constant Ratio of heat capacities, C_p/C_v
L	Length Liquid flow rate
L_c	Cross-sectional length of adsorption bed
L_v	Limit of visibility of visual range
LOT	Light-off time (catalyst)
M	Molar mass (molecular weight)
M_w	Molecular weight
m	Mass Index of refraction
MB	Million Btu
N	Mass transfer per unit time and unit area Number of particles per unit volume Number of particles under given size Number of compartments in a baghouse
N_e	Number of effective turns in a cyclone
N_f	Impaction number
N_t	Number of transfer units
n	Number of particles per differential size
P	Pressure
PM	Particulate matter
p	Exponent in wind velocity profile equation Pressure
Q	Mass emission rate, mass per unit time Volume flow rate, volume per unit time
Q_h	Heat emission rate, energy per unit time
Q_p	Instantaneous mass emission (puff), mass
q	Electric charge on a particle Emission source strength per unit length Quantity of heat transfer
R	Ideal-gas constant Radius
Re	Reynolds number, $\rho VD/\mu$
R_u	Universal gas constant
r	Radius (of particle)
S	Filter drag Separation distance
SCA	Specific collector area, ft ² /1000 acf
SR	Stoichiometric ratio
s	Stability parameter in plume rise
T	Temperature
T_{frac}	Fractional light transmission
$T_{1/2}$	Half life
t	Time
u	Internal energy Wind speed
V	Velocity Volume Voltage
v	Specific volume
W	Mass of adsorbent Width
w	Drift or migration velocity Logarithm of particle diameter Work interaction

X	Liquid-phase mole ratio
	Adsorption capacity, mass/mass
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

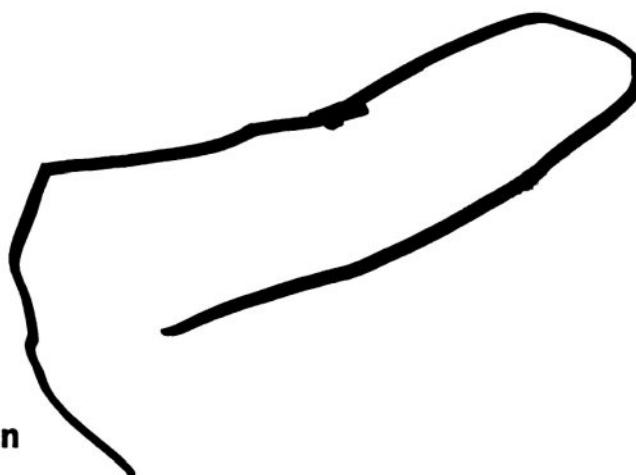
Greek Symbols

Γ	Adiabatic lapse rate
η	Efficiency
Θ	Polarizability
θ	Potential temperature
λ	Lambda, inverse of equivalence ratio
	Wavelength
μ	Viscosity
μm	Micrometer
ρ	Density
ρ_e	Electrical resistivity
v	Ion velocity
σ	Dispersion coefficient
	Extinction coefficient
	Standard deviation
ϕ	Angle
	Equivalence ratio

Subscripts

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

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. A major cause of air pollution is combustion, yet combustion is essential to life as we know it. 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 fuels, 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 person who sold and burned the outlawed coal. Under Richard II (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 are the

fouling and degrading of our environment. One of the earliest legal attempts to control air pollution in the United States appears to be a 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. As recently as 1991, Mount Pinatubo in the Philippines erupted, killing 200 people and emitting particulates and sulfur dioxide 25 miles high into the atmosphere, creating worldwide weather and climatic influences. Although the total global production of many gases and particulate matter recognized as pollutants is much greater from natural sources than from anthropogenic sources, global distribution and dispersion of those pollutants result in lower average concentrations than might exist near anthropogenic sources. By precipitation, oxidation, and absorption into the oceans and the soil, the atmosphere can cleanse itself of most known pollutants given sufficient time [2, 3]. Yet data collected in the last 20 years suggests that concentrations of gases such as carbon dioxide and chlorofluorocarbons (CFCs) are increasing, with potential consequences such as global warming and increased intensity of ultraviolet radiation due to deletion of the ozone layer in the stratosphere. In addition, anthropogenic-generated pollutants are usually concentrated in the more populated, urbanized regions of the world. In the United States alone, more than 150 million metric tons of gaseous, solid, and liquid waste products were discharged into the atmosphere in 1994. Currently the rate at which pollutants are discharged into the atmosphere in highly populated regions at times exceeds the local cleansing rate of the atmosphere.

1-2 Air Pollution Episodes

Although limited air pollution was experienced as early as 1272, it was documented as a major problem only in relatively recent years (i.e., the late 19th and the 20th centuries), considering the history of humankind. During a fog in London as far back as 1873, 268 unexpected deaths from lung-related illnesses were reported. In December 1930, a heavily industrialized section of the Meuse Valley, in Belgium, experienced a severe three-day fog during which hundreds of people became ill and 60 died—more than 10 times the normal number. During a thick nine-day fog in January 1931, 592 people in Manchester and the Salford area of England died—again a large increase in the death rate. In 1948, in Donora, Pennsylvania, a small mill town dominated by steel and chemical plants, a four-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. 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. 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 decrease the burning of soft coal [4]. We have since recognized that these "fogs" were also air pollution episodes that contained pollutants that assisted in creating a dense haze or foggy-like condition. The combination of smoke and fog characteristic of many of these historic episodes has been referred to as "smog." In situations where hydrocarbons, nitrogen oxides, and sunlight are present, these episodes are worsened by the formation of photochemical smog. The smog conditions of Los Angeles, New York City, Chicago, Mexico City, and other large urban areas around the world are widely publicized in today's press.

Although similar episodes have not been reported in the United States in the last 30 years, there are a substantial number of areas that have unacceptable air quality during certain periods of the year. In 1995 in the United States, there were a number of cities, counties, or metropolitan areas in violation of national air quality standards for specific air pollutants. These locations included 77 areas for ozone, 36 for carbon monoxide, 82 for particulate matter, 43 for sulfur dioxide, 11 for lead, and one for nitrogen dioxide [5]. Concentrations of ozone in the South Coast basin of California (Los Angeles area) exceeded the ozone standard 143 days in 1992 with concentrations as high as 0.30 parts per million by volume (ppm) compared to the air quality standard of 0.12 ppm. On the positive side, the number of exceedances in that area has progressively decreased to 83 times in 1996 with a high of 0.26 ppm. (See <http://www.aqmd.gov/smog/> for current air quality information on the South Coast Air Quality District.)

The misuse of air resources is evident throughout the world. Urban air pollution is an increasing problem in Latin America and the Caribbean due primarily to the rapid expansion in the size and industrialization of the urban population. Areas like São Paulo, Brazil; Santiago, Chile; and Mexico City, Mexico frequently exceed their air quality standards. In these areas, the World Health Organization (WHO) guidelines for particulate matter (60 to 90 $\mu\text{g}/\text{m}^3$ annual geometric mean) were exceeded with concentrations that were up to six times the standard during the period of 1983–1987 [6]. Similarly, concentrations of particulate matter in Amman, Jordan, have been found to be 2–3 times WHO guidelines [7]. During 1991, concentrations of ozone in Mexico City exceeded the Mexico standard (0.11 ppm) on 307 days. In March 1992, the ozone concentration in Mexico City reached 0.475 ppm, nearly four times the standard [8].

The continued development of synthetic chemicals has also resulted in more emphasis worldwide on the safe handling of toxic materials that can be emitted from the off-gases from processes during manufacturing or during accidental releases. A recent accidental release was the Bhopal, India, accident in which methyl isocyanate vapor was released killing more than 2000 people.

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. In 1974 world population reached 3.9 billion, and grew to the awesome figure of 5.6 billion in

1993 with an estimated annual growth rate of 1.6 percent. 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.

For developed or developing countries, there appears to be a close relationship between the gross domestic product (GDP) per capita and energy consumption per capita [9]. This is illustrated by recent data for selected countries, shown in Table 1-1 [9,10]. The values represent 1989-1991 estimates. 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. Historically, this increase in energy consumption has also increased the emission of pollutants into the environment. Our ability to maintain a sustainable environment for the future clearly depends on the success of our efforts worldwide to reduce the energy requirements needed to produce the products we have come to enjoy and to find new and improved means of reducing or eliminating the emission of pollutants from our sources of energy.

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. Since the 1960s in the United States, as the public has become increasingly concerned with environmental problems, air

TABLE 1-1 Comparison of Energy Consumption by Country

Country	Gross Domestic Product [11] (\$/Capita)	Commercial Energy Consumption [10] (Million Btu/Capita)	GDP Energy
Zaire	180	2	90
China	370	26	14
India	380	9	42
Chile	2,500	34	73
Russia	3,220	191	17
Saudi Arabia	5,800	168	35
United Kingdom	15,900	139	114
France	18,300	104	176
Canada	19,400	281	69
United States	19,500	273	71
Japan	29,774	111	268

Based on estimates from 1989-91.