Introduction to

Industrial Gas Cleaning

F. A. L. Dullien

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Department of Chemical Engineering
University of Waterloo
Waterloo, Ontario, Canada

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To the memory of Werner Strauss

Preface

Introduction to Industrial Gas Cleaning evolved from a set of class notes for teaching at the University of Waterloo, which were revised over a period of almost ten years. The course, "Air Pollution Control," is offered to fourth year chemical engineering students as an elective in the second semester. These students have already had physics, fluid mechanics, chemistry, and physical chemistry, which may be regarded as the most useful background subjects for an easy grasp of the physical and chemical principles involved in the functioning and design of gas cleaning equipment.

Throughout the book, great care has been taken to define the terms used, to explain the physical and chemical principles, to state the assumptions made, and to go through the mathematical developments in detail. This approach to the subject has resulted in a rather rigorous treatment, which at the same time is readable, as attested by many streams of chemical engineering students who used the class notes that formed the basis of this book. The text can be used in a second semester junior or senior course in air pollution control or industrial gas cleaning for engineering or science students. It is also useful as a reference in a graduate level course or for engineers, scientists, technicians, managerial personnel, or government officials involved in air pollution control and/or gas cleaning problems.

The teaching of air pollution control at the University of Waterloo was introduced in 1974 at which time there were very few, if any, suitable textbooks. The first edition of the reference text *Industrial Gas Cleaning* by W. Strauss was chosen at that time as the main source for this course, owing to its solid technical content. Some of the material presented in that book was gradually made more suitable for teaching purposes by working out numerical examples, deriving formulas, and in doing so, stating and discussing relevant assumptions and elaborating on the physical and chemical principles involved. Simultaneously, a great deal of material from other sources was incorporated into the class notes and then into this book. Throughout the book, the time-honored principles applied in engineering textbooks have been adhered to. Presentation of purely theoretical approaches that do not have direct impact on practical design has been kept to a minimum.

Thanks are due to my colleague Dr. D. R. Spink, who initiated the air pollution control course and with whom I often exchanged views on the subject matter of this course, and to the hundreds of chemical engineering students who took the course and who contributed to the development of this text by their questions and criticisms. The professional help of Dianne E. Taylor-Harding in correcting and completing the references is gratefully acknowledged. For the illustrations, thanks are due to Mr. Rinze Koopmans, and for the excellent typing of the final manuscript, the credit goes to Mrs. Susie Bell. The invaluable assistance of Ann Collins in compiling the index is gratefully acknowledged.

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Introduction

1.1 Sources of Air Pollutants

Air pollution may be either natural or man-made. Recently, there has been a tendency by the media to underemphasize the extent of natural air pollution, which, nevertheless, is very great. Forest fires, volcanic eruptions, ocean spray, biological decay, dust storms, pollens, etc., represent vast sources of air pollutants. Natural pollution, on occasion, has caused major environmental readjustments, because it has often proved to be disastrous to plant and animal life; however, life on the planet went on all the same. The effects of man-made air pollution may either be limited to an area or region of varying but finite size or may have far-reaching consequences for life on the entire globe by threatening to alter the global climate. Air pollution problems are mostly of the limited character, but as they arise near densely inhabited areas, they have both harmful and irritating effects.

Most of the air pollution originates from combustion processes, which include power stations, space heating, and motor vehicles. Smelting and other mineral processing operations are important contributors as is the manufacture of steel, coke, lime, ceramics, and cement. Mining and quarrying and chemical industries are also important contributors. Special problems are presented by noxious odors emanating from certain chemical plants as well as from operations such as blood drying, offal rendering, tanning, food processing, glue manufacturing, and fish meal preparation, pig and cattle transportation, and spreading of manure in the fields.

The contributions to air pollution by various sectors as well as the nature and the emission factors of various air pollutants in the United States are

Table 1.1 Estimated Air Pollution Emissions in the United States in 1975[a]

	10^6 (ton/year) and percentage					
	Particulates	Sulfur oxides	Nitrogen oxides	Hydrocarbons	Carbon monoxide	Total
Transportation	1.3 (0.6)	0.8 (0.4)	10.7 (5.3)	11.7 (5.8)	77.4 (38.3)	101.9 (50.4)
Fuel combustion, stationary	6.6 (3.3)	26.3 (13.0)	12.4 (6.1)	1.4 (0.7)	1.2 (0.6)	47.9 (23.7)
Industrial	8.7 (4.3)	5.7 (2.8)	0.7 (0.3)	3.5 (1.7)	9.4 (4.6)	28.0 (13.8)
Solid waste disposal	0.6 (0.3)	<0.1 (~0)	0.2 (0.1)	0.9 (0.4)	3.3 (1.6)	5.0 (2.5)
Miscellaneous	0.8 (0.4)	0.1 (~0)	0.2 (0.1)	13.4 (6.6)	4.9 (2.4)	19.4 (9.6)
Total	18.0 (8.9)	32.9 (16.3)	24.2 (12.0)	30.9 (15.3)	96.2 (47.6)	202.2 (100.0)

[a]EPA (1976).

shown in Table 1.1 (EPA, 1976). This information is not up-to-date, but is nevertheless typical and informative. The total amount of air pollutants generated in North America today can be estimated in excess of 200×10^6 tons a year. This closely corresponds to the mass of a 1000-ft-high mountain occupying an area of one-tenth of a square mile. As the bulk of the pollutants consists of gases, the amount of pollutants is more impressively stated as gas volume: it would cover an area of 14×14 km with a 1-km-high gas blanket.

1.2 Classification of Air Pollutants

There are several different classifications of air pollutants, all of which may be valid. The broad classification given here is used throughout this text. According to this, air pollutants may be subdivided into (1) particulate matter, (2) gases and vapors, and (3) odorous substances.

Particulate matter may consist either of liquid droplets or solid particles. Several different classifications of airborne particulate matter exist, which sometimes result in ambiguous terminology. For example, the following two classifications of terminology are in use:

Industrial terminology		
Coarse dust	> 100 μm in diameter	Solid
Fine dust	1–100 μm in diameter	Solid
Spray	> 10 μm in diameter	Liquid
Mists	1–10 μm in diameter	Liquid
Fumes and smoke	0.001–1 μm in diameter	Solid or liquid
Meteorological terminology		
Rain	> 500 μm in diameter	Liquid
Drizzle	200–500 μm in diameter	Liquid
Mist	80–200 μm in diameter	Liquid
Clouds and fog	2–80 μm in diameter	Liquid
Smog	0.1–2 μm in diameter	Liquid

It is apparent that in industry the term "mist" means a very fine fog-like spray, whereas in the jargon of meteorology, it means a fine rain that is coarser than fog.

All airborne particulates in the range of a particle size of 0.001–100 μm form aerosols. The definition of aerosol is a "disperse system with a gas-phase medium and a solid or liquid disperse phase." The scientific background for the separation of particulates from gases is provided by the science of aerosol mechanics.

The gaseous and vapor-like pollutants may be subdivided into these categories:

- Sulfur-containing compounds (i.e., SO_2 and H_2S) that oxidize into SO_3, H_2SO_4, and MSO_4 (M, metal)
- Nitrogen-containing compounds (i.e., NO and NH_3) that oxidize into NO_2 and MNO_3 (M, metal)
- Organic compounds (i.e., C_1–C_5) that oxidize into ketones, aldehydes, and acids
- Oxides of carbon (i.e., CO)
- Halogens and halides (i.e., Cl_2, HCl, HF, and F_2)

Odorous substances may have a variety of different origins. They may be present in extremely low concentrations where they may defy any attempt to identify their chemical nature.

1.3 Effects of Air Pollutants

Air pollutants have many harmful effects that may be categorized in a number of different ways, for example:

1. Reduction of atmospheric visibility
2. Interference with the weather (in a subtle way)
3. Materials damage (metals, building materials, protective coatings, etc.)
4. Reduction of indoor air quality
5. Damage to vegetation and life in lakes (smelters and power plants, smog, etc.)
6. Biological damage (pathological effects, carcinogenic effects, etc.)

Volumes have been written in the technical literature on the effects of air pollutants. The interested reader is referred to the specialized literature [e.g., Stern (1976)].

In the light of the numerous harmful effects of air pollutants, air pollution control is obviously necessary.

1.4 Air Pollution Legislation and Enforcement

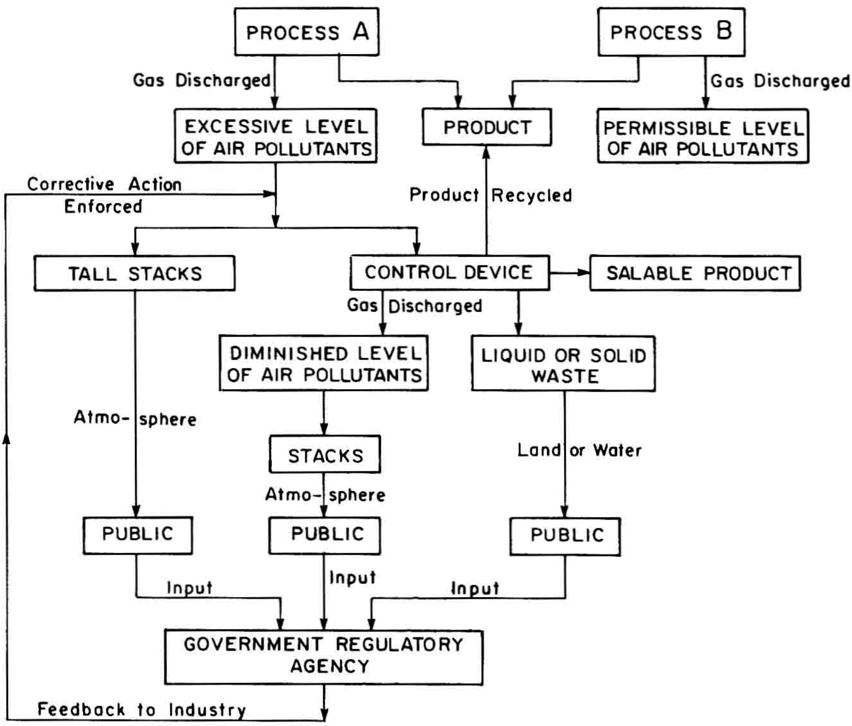
The extent of air pollution control, however, is something to be determined in each particular situation, and this poses a lot of problems. Whereas the moral obligation on the part of industry to control its emissions is undisputed by all responsible management, it is the first responsibility of the management to assure survival and success of the company in a highly competitive economy. Air pollution control, being expensive, adds to the cost of the products, and so it may jeopardize the competitive position of a company. This is one of the reasons why air pollution control cannot be left up to individual companies but must be legislated, and the law enforced evenhandedly. Air quality standards (AQS) have been established to define levels of air quality by certain air quality criteria (AQC) to protect the public health. Secondary AQS define levels of air quality to protect the public welfare from any adverse effects of a pollutant. Different countries, even different states in the United States, have different AQS that are broken down to the level of various pollutants. The reader may find more detailed information on this subject in the current literature (e.g., Licht, 1980; Strauss, 1975). The enforcement of air pollution legislation is generally done by governmental air pollution control agencies, which work with both the industry and the public. Complaints about air pollution problems usually originate with the public, who through political pressure has the power to force the closing of an operation unless it is satisfied with the degree of air pollution control applied there.

1.5 Means of Air Pollution Control

There are essentially three broad categories of methods of air pollution control, classified on the basis of the philosophy of the approach to the problem of prevention of air pollution. These are presented in the order of increasing ultimate effectiveness.

First, historically the idea was both to move the pollutants as far from the plant as possible and dilute them as much as possible. This was accomplished by using tall stacks, some of which are as high as 350 m. While tall stacks usually do the job required of them, they are expensive

Figure 1 Schematic functioning of air pollution control.



and also simply export the pollution problem somewhere else, where it may or may not cause damage, as the case may be. The tall stacks of power plants emitting SO_2 have been responsible for the occurrence of "acid rain," sometimes thousands of kilometers removed from the stacks.

The second approach consists of the use of the control devices, the purpose of which is to (partially) remove the pollutant, once formed, from the industrial gas before the gas is discharged to the atmosphere. The bulk of this textbook deals with the physical–chemical principles involved in the operation and design methods of control devices. The pollutant, once removed, if not noxious or otherwise damaging to the environment, can be discharged into a body of water, dumped or used as landfill. The pollutant sometimes represents a portion of the product, and after collection it is recycled and added to the product. There is always an incentive to turn the pollutant into a salable product in order to be able to pay for the cost of the air pollution control system.

Third, alternate processes to obtain the desired product without causing any air pollution should be listed as potentially the best way of handling the problem. The alternate processes, however, must be competitive or else the cost aspect cancels any possible advantage these approaches may promise to offer. The scheme of air pollution control is depicted diagrammatically in Fig. 1.1.

1.6 Selection of the Control Device

A survey of the table of contents of this text indicates the existence and availability of a large number of different air pollution control equipment, many of which work on the basis of different principles. A large number of factors must be considered before selecting the type of equipment that is most suitable for the particular air pollution problem to be solved. In addition to the first two obvious criteria (i.e., pollutant removal and cost effectiveness), there are many less obvious but equally important aspects of the process/device to be scrutinized. A very important decision to make is whether to use a "wet" or "dry" process. Another important aspect is whether both particulates and gaseous pollutants need to be removed simultaneously. More often than not a number of different control devices need to be used, one after the other, forming a system, in order to achieve the desired cleaning effect.

The starting point in tackling the air pollution control problem is a good knowledge of the nature and the amount of the pollutants present, obtained by source sampling and subsequent analysis of the sample. The temperature, the humidity, and the dewpoint, as well as the quantity of the gas to be treated, must be known. Start-ups, shutdowns, and possible fluctuations in the gas flow and in the pollutant loading must be taken into consideration. Materials of construction must be selected on the basis of temperature, corrosion, and erosion hazards. In addition to the cost of purchase and installation of the system, operating expenses must also be considered. A very important contributor to the operating expenses may be the pressure drop in the system. Another contributor is the cost of maintenance. Trouble-free operation also translates into savings. Safety aspects represent another very important point to consider. Often it is necessary to build a pilot plant before manufacturing the full-scale unit.

Air pollution, in general, and air pollution engineering, in particular, have been covered extensively in the literature. In addition to the textbooks already mentioned in this chapter, the reader may find useful, although inevitably incomplete, this list of reference texts: Hesketh, 1979; Theodore and Bounicore, 1976; Satriana, 1981; Noll and Duncan, 1973; Calvert and Eglund, 1984; Henzel *et al.*, 1982; Storch *et al.*, 1979; Cooper and Alley, 1986; Schifftner and Hesketh, 1983; Cheremisinoff and Young, 1975, 1977; Jimeson and Spindt, 1973; Young and Cross, 1982; Ogawa, 1984; Stern *et al.*, 1984; Friedlander, 1977; Fuchs, 1964; Hidy and Brock, 1970; Sanders, 1979; Liu, 1976.

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