MARTIN CRAWFORD

Air Pollution Control Theory

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MARTIN CRAWFORD

Professor of Engineering
University of Alabama in Birmingham

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**AIR
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PREFACE

Air pollution is a topic which, among many others, has been at the forefront of social concern for the past several years. Most of this concern, as far as the general public is concerned, has been directed toward the health, distributional, and regulatory aspects of the problem. To all appearances, the public has given little thought to the technological aspects of reducing emissions into the atmosphere. This may be due in large part to the fact that there has been no publication available which provides insight into the mode of operation of the various devices for removing pollutants prior to emission into the atmosphere.

The term *air pollution control* is capable of two interpretations. To the public at large it means probably the limitation or prohibition of emissions by force of law. Inherent in this interpretation is the determination of which substances should be limited and to what extent they should be limited, which requires determination of the effects of each substance on health, damage to property, and esthetic values. The interaction of different pollutant substances must also be considered. These areas of air pollution control have been extensively explored in the past several years.

In the second meaning of air pollution control, which is the one employed in this book, the word *control* is used in the sense of prevention. What means are available to prevent air pollution from occurring? Aside from shutting down all polluters, which would mean disabling our economy and disrupting our way of life, there are means available or potentially available to remove all pollutants to the extent necessary to prevent serious atmospheric contamination. These means take the form of certain devices which are subject to engineering analysis, and which can be designed, built, installed, and operated to achieve the desired result, but not without problems. In dealing with such problems, we need engineers who are trained to understand these devices; this book is designed to help provide such training.

A well-established branch of chemical engineering is that of gas cleaning. So how does air pollution control, in the sense used in this book, differ from gas cleaning? In truth, air pollution control lies within the discipline of gas cleaning. Nevertheless, the problems encountered in the design of control devices tend to be much more difficult than those associated with the usual gas-cleaning equipment. In processes where a solute is to be separated from a gas, the initial solute fracton is normally large and 90 to 99 percent removal is generally considered good practice. In air pollution control work, the initial concentration is usually quite low and the same 90 to 99 percent removal is required. Thus, in a sense, air pollution control takes up where ordinary gas cleaning leaves off.

This book is intended first of all as a textbook for use in a course in air pollution control theory. Such a course can be designed for senior engineering students or for graduate engineers. It is intended that the student gain familiarity in the following areas: (1) qualitative description and quantitative evaluation of the problems associated with control of air pollution; (2) understanding of the mode of operation of the various control devices; (3) evaluation of the performance of the various control devices; (4) evaluation of the performance of the total pollution control system, which may include several control devices, as well as the associated ductwork, hoods, and fans; (5) the methodology of gaining better insight into the operation of the devices and improving them; and (6) the methodology of design of air pollution control devices. The book attempts to deal with each of these areas of study.

It is hoped that this book will be of use to practicing engineers in the air pollution field. Its potential usefulness to such engineers is more seminal than remedial; that is, it should provide insight and inspiration toward arriving at new designs more than toward correcting defects in existing designs. The intent is to provide instruction in bringing theoretical insights into practical design and analysis of the various devices involved. It is in no way a handbook or compendium of practical solutions to practical problems.

The purpose of this text is to apply certain fields of engineering analysis, notably fluid mechanics, thermodynamics, heat transfer, dynamics, and electrodynamics, along with certain phases of chemistry and physics, to the rudimentary analysis and design of air pollution control devices. In this sense, it functions in the same way as texts on internal combustion engines, turbomachinery, or steam power plants which are used in senior mechanical engineering courses on these subjects, to mention three examples. Such books seek to bridge the gap between pure theory, as it is taught on the undergraduate level, and engineering practice in the field. Although such books are generally anchored equally well on the theory and practical sides of the gap, they carry the reader only so far into the practical field. To the author's knowledge, this is the first textbook which attempts to bridge the gap between theory and practice in air pollution control. Even a casual perusal shows that this book is anchored much more firmly on the theoretical side, which is a consequence of the newness of the approach, time limitations in developing the material, and the fact that much practical data in the field are still hoarded as proprietary information by the various companies active in developing air pollution control devices. The author hopes that future books will appear, including perhaps a later edition of this one, which will provide significantly greater emphasis on the practical aspects of applied theory.

The author believes that air pollution control theory is not the same thing as the combined total of the theory of operation of each of the available control devices; that is, in this sense, the whole is greater than the sum of its parts. This viewpoint can be defended: First, there are aspects of air pollution control which are common to all control devices and which can be treated separately from any particular device. Second, there exists the possibility that new devices may be invented from time to time and take their place in the theory. Third, there are synergistic effects involving the interaction of various control devices and other elements in any air pollution control system. And fourth, there is that branch of knowledge dealing with the selection of a particular control device to use in the first place.

There exists or can exist a field of air pollution control theory, which can take its place among the many specialized fields of engineering. Such a field is as difficult, challenging, and important to an industrial society as any other field. Whether or not this field is allowed and encouraged to develop depends upon the priorities and expectations which society places on the engineering profession and upon the resources allotted to it.

The material included in this text should be adequate for a course sequence totaling six quarter-hours credit. With some supplementation it should suffice to handle a course sequence of six semester hours. A course of three semester-hours credit can cover perhaps two-thirds of the book, say, to Chapter 9 or 10.

The author wishes to express his gratitude to the School of Engineering, University of Alabama in Birmingham, for its support during the preparation of the manuscript for this work. He is also grateful to his former students for their many helpful comments and criticisms. Particular thanks are due to Dr. E. R. Greene, Jr., for a number of illuminating discussions regarding technical matters, and to my father, Guy Crawford, for reading the manuscript.

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INTRODUCTION

With this chapter begins a study of many of the theoretical aspects of the science of reducing the level of pollution of our atmosphere. Predominantly, what is studied is the removal of pollutants from various effluent streams discharging into the atmosphere, a process which can be referred to as *depollution.* The vastly more desirable method of replacing a polluting process with a nonpolluting one is not treated here to any extent; this can be handled best in a detailed study of the particular process involved. The current chapter deals with the subject of air pollution control in a general way; subsequent chapters become more specific and more mathematical.

1-1 ROLE OF AIR POLLUTION CONTROL IN MODERN SOCIETY

Industrialization has provided humanity with many material and social benefits. At the same time it has brought in its wake many material and social problems. One of these is pollution of the environment. Most ecologists recognize pollution as a serious threat to the quality of our life and possibly to its very existence. Interest in environmental concerns has become intense in recent years, with much pressure being placed on public and corporate officials to alter policies and practices which in the past have resulted in degradation of the environment. Court actions and legislation have required industrial concerns to be more careful of pollution. It appears hopeful at least that in a few years our environment will be cleaned up to a considerable degree. Even so, much remains to be done, and many polluting practices continue to exist. There is a negative side to this concern for the environment. Environmentalists have succeeded in blocking many projects whose need to society is evident. These actions may be meritorious in most cases in that proper concern for the environment was not given in the planning of the project or that alternative plans should have been considered. Nevertheless, a better decision-making procedure needs to be developed, which will give proper concern to the effect on the environment but not allow a small group to block construction once a decision has been made.

Since pollution is concomitant with most industrial activity, methods of controlling it must be employed. The best method of control is to avoid pollution in the first place by replacing the present process with one which does not pollute. Usually this is not feasible, and so some method of control must be installed. Generally, the pollution control method adds to the cost of the process, and, for the most part, the added cost is passed on to the consuming public. In a few lucky instances, material of value will be recovered in the pollution control process, so that a net saving will result. In most such cases, however, material recovery will already be practiced and the degree of collection efficiency that is most economical for material recovery will be completely inadequate for effective pollution control.

When the social cost of pollution is considered—damage to health of the people in the community, damage to health of workers in the plant, damage to property, and damage to aesthetic values—a high degree of pollution control is nearly always indicated. Since the public pays the cost of pollution or its control, one way or the other, it seems reasonable that the public should insist that pollution control measures be installed where needed. This can best be done by requiring those who pollute to bear the full social cost of their pollution.

The following types of pollution are generally recognized. Some overlap exists between the different types.

Water pollution The presence, in concentrations higher than normal, in natural waterways (lakes, streams, rivers, and oceans) of dissolved or suspended foreign material, such as silt, chemicals, fecal matter, metallic elements, organic material, or nutrients.

Air pollution The presence in the atmosphere of solid particles, liquid droplets, or gaseous compounds which are not normally present or which are present in a concentration substantially greater than normal.

Waste pollution The presence on land or water of solid material, organic or inorganic, which has no beneficial qualities.

Chemical pollution The presence in plants and animal tissue, including feed and foodstuffs, of adulterant chemicals which have no beneficial effect.

Noise pollution The presence in the open atmosphere or in a confined space of a noise generally considered undesirable, except possibly by the person responsible for it. In the latter case, noise pollution does not exist in the space immediately surrounding the person.

Thermal pollution The discharge into the environment of a stream of air or water which is at a different temperature from that of the environment at the point of discharge or downstream of this point.

There is room for disagreement as to what constitutes pollution, especially in the case of chemical and noise pollution. For example, some food additives are regarded as beneficial by the manufacturer but as adulterants by some consumers. And a particular noise can be regarded as beautiful music by one person and as a discordant annoyance by another.

The concern of this book is with air pollution, which is described more completely in Sec. 1-3. At this point we shall consider the best results that air pollution control can achieve. It must be recognized that natural processes continually purify the air. Thus if all human sources of pollution were to stop today, the air would eventually be purified to its natural state. It must also be realized that natural processes pollute the air, and that natural air contains a certain level of what would otherwise be regarded as pollutants. Since such a level of pollution is natural and presumably organisms are adapted to it, we shall define polluted air as air which contains any substance in an amount significantly greater than that which appears in natural air. If the substance does not appear at all in natural air, then its presence constitutes pollution. Since water can appear in the atmosphere in all concentrations ranging from almost none to that required for saturation, we shall not regard water as a pollutant. This distinction has important practical consequences inasmuch as the effluent from many stacks discharging into the atmosphere may consist of almost pure water mixed with air and may be mistaken as a source of pollution.

It is possible to achieve virtually complete removal of any polluting substance from any airstream discharging into the atmosphere. Such complete pollution control is too expensive to be seriously considered in most cases, and, in fact, is unnecessary. However, there are situations where pollution control must be virtually complete. Nuclear power plants are a case in point, where radioactive materials must not be allowed to escape in quantities large enough to cause damage. Biological weapons research laboratories are another example where the escape of even the smallest amount of the wrong substances could cause complete catastrophe. In most cases, however, a certain amount of impurities can be allowed to pass into the atmosphere without serious harm. Natural purification processes will then keep the atmosphere reasonably pure. Since the cost of purifying an airstream increases drastically as complete purification is approached, a reasonable balance must be found.

In general, the cost of cleaning a gas stream increases with increasing gas-flow rate but at a rate somewhat less than proportional to the gas-flow rate. For a given amount of collected material, the cost is much less for a concentrated gas stream than for a dilute one; thus it is better to clean the stream before diluting it with additional air if this is possible. It is also more economical to clean a continuous gas stream than an intermittent one, particularly one which is used only occasionally. For these reasons, it is better to require 99 percent control on the effluent from a steel mill than to demand 60 percent control from 30,000 backyard barbecue grills. To be sure, backyard barbecue grills could be proscribed, and life would go on without them. But would the extra cleanliness of our air be worth that much deprivation to that many people? Choices such as this will have to be made. In any event, it is probably impractical to require as complete control over small sources of pollution as over large sources even though the small individual sources are far more numerous than the large ones and their total effluent may equal or exceed that from the large sources.

The question that concerns us most at this point is: To what extent can we reduce the total emissions into the atmosphere if we make the maximum cost-effective use of existing air pollution control technology? By cost effective is meant that degree of control which is beneficial to society as a whole, balancing the social cost of pollution against the cost of the control device. As explained previously, pollution control is seldom cost-effective on any other basis. To answer our question, at least qualitatively, let us assume that one-third of the total emissions is from large factories for which 98 to 99 percent control is feasible, one-third is from medium-size operations where 90 to 95 percent control can be economically obtained, and the remaining one-third is from small plants and individual operations where an average of 60 percent control can be obtained from control measures and elimination of certain unessential operations. Thus, the total reduction of the atmospheric pollution load is estimated to be about 84 percent, which appears to be acceptable as a current goal. It also appears to be obtainable, except possibly in two problem areas: The first problem relates to gaseous effluents from steam-generation plants, whether for power generation or for process and heating steam; the second problem relates to the automobile and other internal-combustion engines. In both cases, the pollutants involved are the oxides of sulfur and nitrogen. Much research is currently in progress on ways of controlling the emissions of these pollutants. Until this research bears fruit, realization of the above goal will not be entirely possible.

What about the future? Assuming that within the next few years we realize a reduction to 15 percent of current emission levels, will we be able to hold to that level indefinitely? To answer this question, one must make assumptions concerning the growth of industrial output, or at least that portion of industrial output which contributes to pollution, and concerning the advance of air pollution control technology. Most industrialists and economists like to predict a doubling of industrial capacity every 10 to 20 years. For example, utility executives frequently indicate that they expect the demand for electric power to double every 10 years for the foreseeable future. Of course, industrial capacity as a whole might not advance quite that fast, but a doubling every 15 years seems reasonable. However, we have now entered what has been called the *postindustrial age*. Much future increase in production may be oriented toward services, which are largely nonpolluting, computer software is a case in point. Also, many future production increases may take place in relatively nonpolluting activities, such as sophisticated electronic gear. Except for obvious pockets of poverty, there is reason to question whether the average American citizen really needs any increase in production. For these reasons, a much lower productivity increase rate may become the order of things. It is unlikely, however, that per capita production will decline as long as our resources hold out. Thus a lower limit to our future growth in industrial capacity is the population growth.

With these factors in mind, we might reasonably project a 4 percent annual growth rate in uncontrolled pollution. This figure corresponds to doubling the amount of pollutants before control every 18 years. To maintain a level after control equal to 15 percent of current emissions will require an average control of 92 percent after 18 years and 96 percent after 36 years. To achieve the latter requirement more advanced pollution control equipment must be developed or polluting activities must be restricted to large factories, where 98 to 99 percent control can be attained with present-day technology.

1-2 SCOPE OF AIR POLLUTION CONTROL THEORY

What is meant by air pollution control theory? And how does it differ from the study of air pollution control devices? Many devices are available for removing contaminants from air. These work on a variety of different principles, and in most cases the devices used today are similar to ones developed many years ago. Their designs have evolved over the years as experience was gained with their use and as theoretical insights were arrived at. Some of the more common devices include the settling chamber, the cyclone collector, inertial collectors of various types, filters, electrostatic precipitators, scrubbers, absorbers, adsorbers, combustion chambers, and condensers. Much air pollution control theory is indeed devoted to the study of how these devices operate and how they can best be designed.

The status of air pollution control theory, if limited to the detailed study of the operation and design of various control devices, can be described as one of adolescence; that is, the study of such devices has proceeded beyond the stage of infancy but has not yet reached maturity. By contrast, consider the gas turbine for aircraft application, or, in other words, the jet engine. A tremendous amount of research work has been conducted over the last 40 years to precisely describe the flow paths, boundary-layer development, and heat-transfer rates throughout the various components of the system. A complete bibliography in this area would run to several thousand entries. To be sure, the study of the jet engine is not complete by any means, and research will undoubtedly continue for many years to come. Consider, now, the quantity of research devoted to understanding the various pollution control devices. Some devices have been studied more extensively than others; the electrostatic precipitator has probably received the most attention. Even so, the number of research papers devoted to this one type of control device is only a small percentage of those devoted to the jet engine. Thus, the detailed operation of the electrostatic precipitator is not well understood. Most other air pollution control devices are even less well understood. This pessimistic view of our current knowledge should not obscure the fact that much is known about the operation of these devices.

Air pollution control theory, as envisioned in this book, encompasses the theory of each separate control device, but it is more comprehensive. The various control devices have much in common as to their net effect on the airstream. That is, their performance can be described in terms of a collection efficiency, and each device induces a certain pressure drop in the fluid stream. Therefore, the effect of a control device can be studied without knowing which control device is being used. Several control devices can be used in combination in a system, along with other elements. The interaction of various control devices, of the same type or of different types, with each other and with the other elements in the system can be studied in detail. Studies of this type represent a large portion of air pollution control theory. Studies of the entire system or comparisons of various different systems as to performance and economics fall under the scope of our theory. Finally, any systematic or theoretical means of selecting particular types of pollution control devices is a part of a comprehensive air pollution control theory. This book treats the theory of operation, design, and economic selection of the more common devices and also delves into the broader aspects of air pollution control theory as outlined in this section.

1-3 NATURE OF AIR POLLUTANTS

Polluted air was defined in Sec. 1-1 as air plus one or more constituents not normally present in air or present in greater than normal concentrations. The polluting constituents, or pollutants, can be in the form of solids, liquids, gases, or vapors. Solid and liquid pollutants are referred to as particulates, and these pollutant particles appear quite distinct from the gaseous phase when viewed under the microscope. Gaseous pollutants, on the other hand, exist as individual molecules diffused throughout the air; gaseous pollutant molecules cannot be distinguished from air molecules under the microscope.

The following classifications of polluted air masses are in common use:

Dust A mixture in air of irregular-shaped mineral particles in the size range from 1 to 200 μm formed by crushing, chipping, grinding, or like operations or by natural disintegration of rock and soil. Lint and particles of organic matter are also classified as dust.

Smoke A mixture in air of very fine particles formed by combustion or other chemical processes in the size range from 0.01 to 1 μm. The particles may be irregular in shape if formed of solid material, or they may be spherical if formed by condensation.

Mist A mixture in air of liquid droplets in the size range from 5 to 100 μm in diameter.