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With 285 Figures and 53 Tables

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Preface

This book has arisen directly from a course on Air and Water Pollution Control delivered by the first named author at the Technical University of Berlin. Extractions of this course have been presented in Brazil, Turkey and India. It was at the Indian Institute of Technology of Madras where the first named author got in contact with Professor Varma, who turned out to be a suggestive, cooperative coauthor.

This book is addressed primarily to chemical, environmental and mechanical engineers, engaged in the design and operation of equipment for air pollution control. But it will certainly be helpful to chemists and physicists confronted with the solution of environmental problems. Furthermore it is intended as a text-book for engineering courses on environmental protection.

The goal of the book is the presentation of knowledge on design and operation of equipment applicable to the abatement of harmful emissions into air. The technology of air pollution control is of relatively young age, but it has already achieved a high degree of performance, due to the research and development work invested in the last decades in this field.

The first two chapters deal with environmental protection engineering. A short review of the development of environmental consciousness and of legal actions taken in the last two centuries in Germany is presented. A preliminary last step was made in 1974. Environmental technology has been developed particularly in the last 50 years. The appropriate technology was therefore largely available, when legislation imposed severe restrictions on harmful emissions.

Chapter 3 gives a short survey of air pollution techniques. In Chapters 4 to 7 design and operation of the most important types of dust removal equipment are discussed, namely cyclones, wet dust scrubbers, fibrous filters, and electrical precipitators. A special chapter is then devoted to mist separation, that is not only related to wet dust scrubbing but also to absorption of gaseous pollutants, when the liquid absorbent is dispersed in the gas mixture. In the following Chapters 9 to 12 physical, biological, and chemical processes and the related equipment for the removal of gaseous pollutants are discussed. The technical equipment includes absorbers and adsorbers as well as biological and chemical reactors.

I should like to thank many people, especially my coauthor for his engagement in this work. I am also most grateful to all of my coworkers, the scientific, technical, and administrative personnel of the Institute of Chemical Engineering of the Technical University of Berlin. Special mention deserve Dr.-Ing. R. Spilger, who relieved me of much of the daily routine work, Mrs. Strauss, who typed and retyped the manuscript with never relaxing carefulness, and Mrs. Westphal, who accepted the responsibility for the preparation of a few hundred figures.

Finally, I should like to thank my wife for her never ending patience and love. It is to her that this book is devoted.

To B.B. Berlin, December 1980

Heinz Brauer

Contents

Chapter 1

Introduction to the Problems of Environmental Protection

Contents

1. Environment – Environmental Protection – Environmental Engineering

Through centuries and milleniums, never ending hardships and deeply rooted anxieties as well as hopes for a better future have impressed their signum on man, thereby determining man's behavior, his outlook on life and his environment. Hunger, diseases, inclemency of weather, and destructive natural forces have at all times been man's companions. In order to survive, and in order to shape a better future, with more freedom from want and fear man saw only one possibility of reaction to those formidable challenges: to shape his environment according to his wishes. He engaged himself in a seemingly endless struggle with nature, with his natural environment.

Through centuries and milleniums, man experienced the glory of victory. However small the success was, it encouraged him to carry on his fight. But slowly it also dawned upon him that victory is not only glory, but that victory also encompasses destruction. Finally, man began to realize that the destructive forces he commanded began to shape and misshape his environment to such an extent that his own life and his own future were endangered. Something has gone wrong with this Promethean struggle. Man must learn to control his creative power that can be applied to constructive and destructive deeds as well.

In the language of modern science, man has in certain parts of his environment disturbed or even destroyed an ecological equilibrium of nature. If this continues as in the past, man will destroy natural ecology and thereby the basis of his own life and future. To restore where necessary and to protect the ecological equilibrium in all of his environment, environmental protection has gained priority on the list of works of man.

Science is the offspring of doubts. Man therefore asks what is ecological equilibrium. Is there an ecological equilibrium for the whole earth or only for restricted parts of it? Is this ecological equilibrium a static system or is it, as man tends to assume, a dynamic system? What is the role of natural evolution in ecology and what are the forces behind it? How does man command forces that effect evolution? Can man attach values like good and bad to observed results of evolution within our ecological system? How do we value the disappearance of the dinosaurs at the end of the mesozoic era, about 60 million years ago? Or how do we value the successful fight in many countries of the world, against the mosquito anopheles, the carrier of the malaria parasite that caused the death of millions of people even in our times?

There are far more questions about ecology and its natural equilibrium. There are no easy answers. As a matter of fact, it seems that we are at present not in a position to say clearly and without doubt when to lament changes in our natural environment caused by man's activities. We are not sure any more whether philosophy and religion furnish us with ethical and practicable standards by which we can measure and value the effect of our activities on our environment. Without ethical standards man will be helpless and will be lost in a world he started off to conquer and to shape according to his will.

There are many arguments in favour of a restricted outlook on environment and all its problems. Accepting man as the most prominent and certainly dominating figure of the environment, it may be accepted, that man himself sets the rules for judgement of his own affairs. It localizes environmental problems. Environment is the space of man's activities. With respect to each individual, environment may be interpreted as the world in which our fellow-men live. It is this world, it is our fellow-men that need protection. Environmental protection defined in this way includes ethical aspects.

Environmental protection is a basic necessity for man,
Naturam protegere necesse est.

Man made his strongest impact on his natural environment after he had developed technology, which he used for the creation of a man-made and man-centered technical environment. Technical environment thus stands against natural environment; but this is not necessarily the case. Technical and natural environment must be coordinated to the best of man himself. Man must apply technology not only to the creation of his technical environment but also to the protection of the natural environment. Application of technology to the protection of the environment leads to a new engineering discipline: *Environmental protection* *engineering*. The environment consists of three important spatial elements, which are air, water, and soil. Environmental protection engineering has to protect air, water, and soil against any serious disturbance of its own natural equilibrium. Technology supplies the tools but it is man who has to apply these tools for the benefit of his environment and his future.

The immensity of the engineering problems involved in environmental protection can be deduced from the book by Meadows: "Limits to Growth" [1]. These problems remain widely unaffected by the models applied to the description of cultural, economic, and technological development of the world or parts of it. A team of scientists and engineers from the Netherlands has analyzed and described in detail the environmental problems that have to be solved [2].

Just to get an impression of the monetary consequences of environmental protection the United States of America may be taken as on example. The data are taken from the Journal "United States News and World" in 1970. In this year, President Nixon announced the "Pollution Central Program". For the following five years, it was estimated that environmental protection in the USA required 70 billion US dollars. Of this amount

72% were estimated to be necessary for the introduction and improvement of communal waste water treatment,

14% were estimated to be spent by industry in all fields of environmental protection, and

8,5% for the abatement of emissions from motor cars.

The percentages given are probably the same for all industrialized countries. Waste water treatment will in all cases require the bulk of the expenditure. Air pollution control requires only a relatively small part of the overall expenditure.

The problems of environmental protection can only be solved by the coordinated endeavours of various engineering and scientific disciplines: physics, chemistry, medicine, biology, chemical engineering, and social sciences. For any single discipline it is impossible to solve the problems. Many scientific and engineering disciplines will have to contribute to the solution of the problems. The engineers' contribution will be primarily the development, design, and operation of equipment for the abatement of harmful emissions. It is to this branch of pollution control to which the main part of this book is devoted.

In the following sections it will become clear that environmental pollution is still primarily a local problem. It must be observed therefore that solutions to environmental pollution control cannot be generally applied to the problems in places with different conditions. Local conditions have to be carefully analyzed in search of an optimum solution to the given problem.

2. Sources of Pollutant Emission

Pollutants are emitted from sources defined by their

1. size,

2. strength,
3. species of pollutant.

With a certain simplification, the sources of pollutant emission may be divided into two groups:

1. independent single sources,
2. field of sources.

The first group of emission sources is easily understood. The second group, however, needs explanation. A field of sources is what is sometimes called diffuse sources. When a large number of sources of generally little strength are combined with a unit distinctly separated from the surrounding space, this type of emission unit is called a field of sources. As far as spreading and distribution of the pollutants in the environment is concerned, the whole unit and not the individual elements have to be considered as a source of emission. Sources of emission contained in a field cannot be considered separately. These sources are very close together and the emissions will be mixed together even while they are still within the spacial dimensions of the source field. Both types of sources, single sources and fields of sources, will be considered in detail.

There are three groups of independent single sources:

1. point sources,
2. line sources,
3. area sources.

The best known point sources are high chimneys. Independent of a visible or invisible plume emerging from the stack, people are convinced that stacks are sources of very strong emissions. Dividing the emission flow rate by the emission area, i.e. the exit area of the stack, the emission flux is obtained. Because of the small exit area, the emission flux of a stack will always be very large. The emission properties of high stacks demonstrate the emission properties of independent point sources:

1. defined locality of emission,
3. great height of emission [m],
3. type of emission,
4. great strength of emission flow rate [kg/s],
5. great strength of emission flux [kg/sm ^{2}].

The height of emission must be seen in relation to houses and technical installations in the surroundings of the point source.

Independent line sources are, for example, waste water conduits, while waste water treatment tanks, harbours, and estuaries may serve as examples for area sources. Fig. 1 presents a view on the largest waste water treatment plant in Germany [3]. The height difference between independent line and area sources and the environment is in most cases of no importance. Because of the relatively large area of these two sources, the emission flux may be relatively small, the emission flow rate and the nuisance to the population living in the surround-

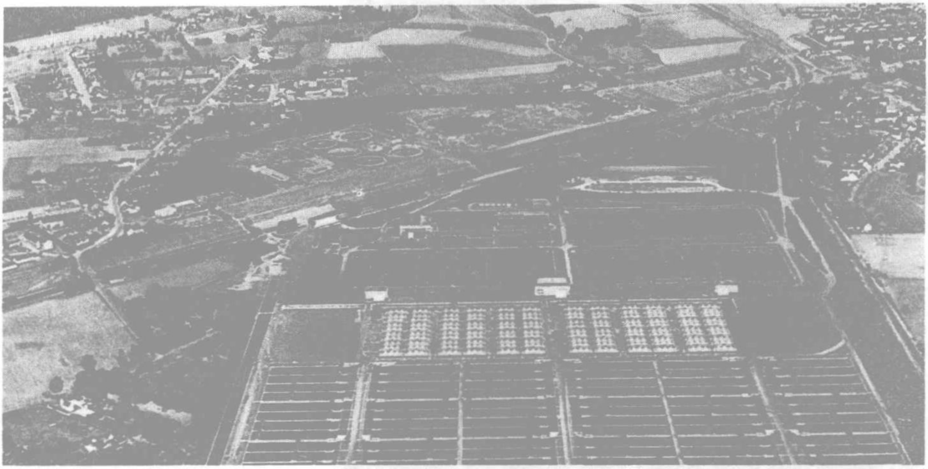

Fig. 1. Largest waste water treatment plant in the Federal Republic of Germany; Emscher treatment plant near Duisburg

ing area may be quite appreciable. The emission properties of independent line and area sources may be given a s follows:

1. defined locality of emission,
2. zero local height of emission [m],
3. type of emission,
4. strength of emission flow rate [kg/s],
5. strength of emission flux [kg/ms·m^2].

The classification of emission sources has been source oriented. But there is also another classification possible based on observations made far downstream of the sources. In many industrial plants, there may be several high stacks close together (Fig. 2) [4]. An observer at point B1 in Fig. 3 can easily identify each emission source with respect to locality, height, type, and strength. For an observer at position B2, however, these properties cannot be determined any more. With increasing distance from the emission source, the emitted pollutants from different sources will disperse in the atmosphere and mix with each other. Emissions and emission sources loose their identy, and with loss of identity, they suffer loss of importance. For all technical measures taken for the abatement of harmful emissions, first of all the source of emission must be identified and its properties must be given as accurately as possible. This proves the advisability of adopting the emission-oriented point of view in the classification of emission sources.

Another advantage of emission-oriented consideration is that the person or company that causes emission or is responsible for it is always in the center of all considerations. Emission-oriented considerations are always source oriented.

Contrary to independent single sources, a field of sources contains a large number of interdependent sources. Outside of the field, the individual sources

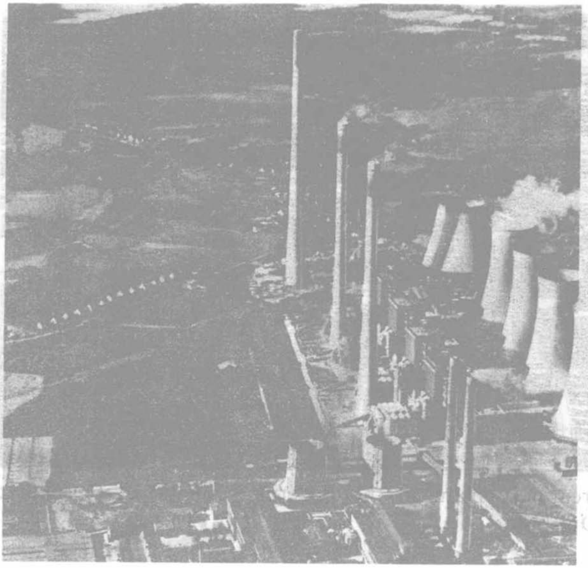

Fig. 2. Industrial complex with several high stacks

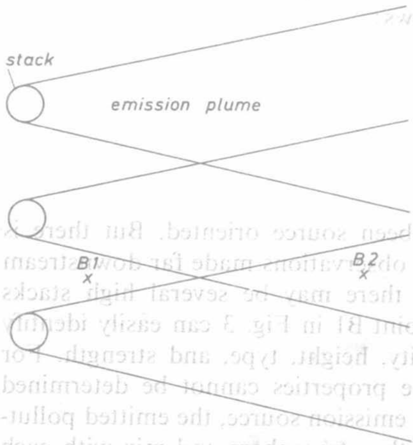

Fig. 3. Schematic representation of pollutant dispersion in the lower atmosphere from a group of high stacks

cannot be identified. An identification of an individual source is only possible within the field. The properties of each individual source may be characterized as follows:

1. defined locality of emission within field sources,
2. type of emission,
3. low strength of emission flow rate.

Comparing these properties with those of independent single sources, one finds no fundamental difference, with the exception of the strength of emission. It is this difference that determines the techniques adopted for the abatement of emissions.

There are three groups of source fields:

1. one-dimensional source fields,
2. two-dimensional source fields,
3. three-dimensional source fields.

A one-dimensional source field is, for example, a traffic highway with trucks and motor cars as individual sources. Two-dimensional source fields may be urban living quarters. Three-dimensional source fields are, for example, industrial plants. In Fig. 4 a photograph of a chemical plant is reproduced [5]. The individual sources of emission of such a field are the numerous flanges and valves. The type and height of emission sources have a strong impact on the degree of pollution of the environment and the harmfulness of emissions to man, fauna, flora, and material objects. As an example Fig. 5 describes the dust emission in the western part of the Ruhr area in Germany classified according to height of all emission sources [6]. It is noteworthy that 50% of the total amount of dust is emitted in the lowest height region from 0 to 10 m. In this region, the dust is primarily emitted by all three types of source fields as well as by independent line and area sources.

It is these emissions at low height that cause serious harm to all living beings and material objects. It is very difficult to prove the exact influence of pollution on death rates of living beings, although this influence is denied by nobody. It is far more easy to prove the devastating influence of pollution on works of art and buildings. The destructive action of sulfur dioxide on the world famous gothic cathedral of the city of Cologne and the temples of Athen,

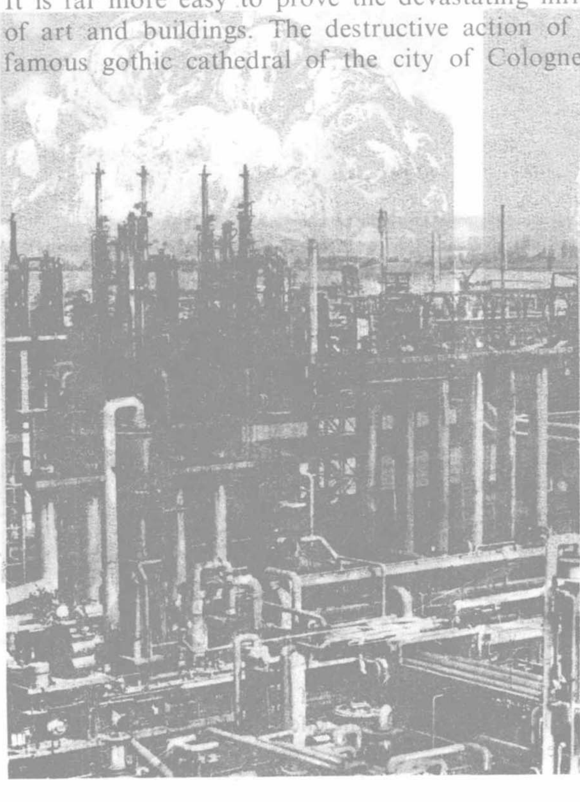

Fig. 4. Chemical plant as an example for three-dimensional source fields

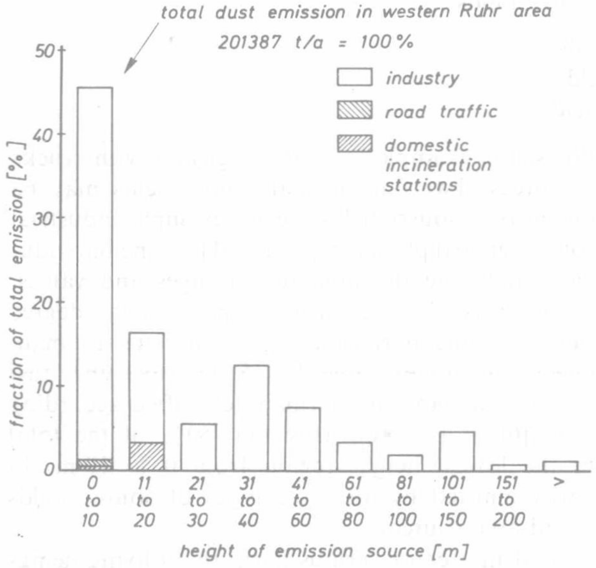

Fig. 5. Classification of dust emission in the western part of the Ruhr area in the Federal Republic of Germany according to height of emission sources

Fig. 6. Porch of Maidens of the Erechtheum on the Acropolis in Athens, showing the effects of air pollution on the statues

Fig. 7. Head of a bronze statue in Munich showing the effects of air pollution

two and a half thousand years old monuments of European cultural development, may serve as examples [7]. Fig. 6 gives a photographic view of the Porch of the Maidens of the Erechtheum on the Acropolis in Athens [8]. The sculptures are seriously damaged by pollutants which are emitted into the air. Another example of the destructive action of air pollutants is shown in Fig. 7. Reproduced is the photograph of the head of a bronze statue in Munich [9].

3. Environmental Pollution

It has already been mentioned that for a simplifed discussion of the pollution problems, the environment will be divided into the three elements: air, water, and soil. For each of these elements pollution due to natural and anthropogenic activities will be discussed.

3.1 Air Pollution

Air pollution is due to natural and anthropogenic sources, that is to man's activities. The pollutants may be gases as well as liquids and solid particulate matter. They are detrimental to man, to fauna, to flora, and to material objects of our world.

The World Health Organization of the United Nations defines air pollution and pollutants in the following way: Air is polluted when one or several pollutants are present in the atmosphere at such a concentration and for so long a time that they are harmful to man, animals, plants and material property, cause harm or reduce well-being or disturb appreciably its application.

In a more simple way, it may be said that air is polluted when its composition deviates from that of "pure air". As there is no possibility for a quantitative definition of pure air, the composition of dry air for usual conditions at sea level is accepted as a standard for pure air. This composition is given in Table 1. It includes certain elements like carbon monoxide and nitrogen oxides, which are dangerous pollutants when present in the air beyond a defined concentration. It is always the concentration – the dose – that makes a pollutant.

Paracelsus[1], a famous physician in the sixteenth century, stated, that almost any substance may be either beneficial or harmful to man, depending on the amount used and the way it is combined with other substances.

Some of the important pollutants found in the air are listed in Table 2. These pollutants are emitted by natural sources or they are due to man's activities, i.e., they are emitted by anthropogenic sources. The data given in Table 2 are presented graphically in Fig. 8. According to these data emissions from anthropogenic sources are almost negligible when compared with emissions from natural sources. However, the environment is endangered predominantly by the few percent of global emissions from anthropogenic sources. The differ-

1 Philippus Theophrastus Bombastus von Hohenheim, 1493–1541, was a famous Swiss-German physician and scientist. He was later called Paracelsus. He made important contributions to the development of experimental research.

Table 1. Composition of dry air at sea level conditions

Component	Concentration ppm = cm^3/m^3 air	
Nitrogen	789,900	990,300 ppm = 99.03%
Oxygen	209,400	
Argon	9,300	
Carbon monoxide	315	
Neon	18	
Helium	5.2	
Methane	1.0–1.2	
Crypton	1.0	
Nitrous Oxide	0.5	
Hydrogen	0.1–0.5	
Xenon	0.08	
Nitrogen dioxide	0.02	
Ozone	0.01–0.04	
Ammonia	0.01	

Table 2. Global emissions from natural and anthropogenic sources [10, 11, 12, 13, 14]

Substance annual global emission in tons	Percentage of emissions and sources: Natural sources		Anthropogenic sources	
1. Sulfur dioxide SO_2 $44 \cdot 10^9$	90%	Decomposition of organisms (H_2S) Volcanoes oceans	20%	70% Energy; 28% Industry
2. Carbon monoxide CO $3.5 \cdot 10^9$	90%	Forest fires Oceans Forests	10%	75% Traffic, cars; 15% Industry; 10% Waste disposal
3. Carbon dioxide CO_2	—			Predominantly from incineration processes
4. Nitrogen oxides NO_x $0.82 \cdot 10^9$	94%	Various NO formations lightning etc.	6%	55% Energy; 40% Traffic
5. Ammonia $2.5 \cdot 10^6$	99%	Decomposition processes	1%	Industry fertilizer
6. Hydrocarbons	96%	Methane from decomposition processes Terpene from coniferous forests	4%	65% Traffic, refineries; 25% Industry
7. Dust and aerosols	94%	Salts from the oceans Dust caused by wind volcanos	6%	40% Energy; 60% Industry

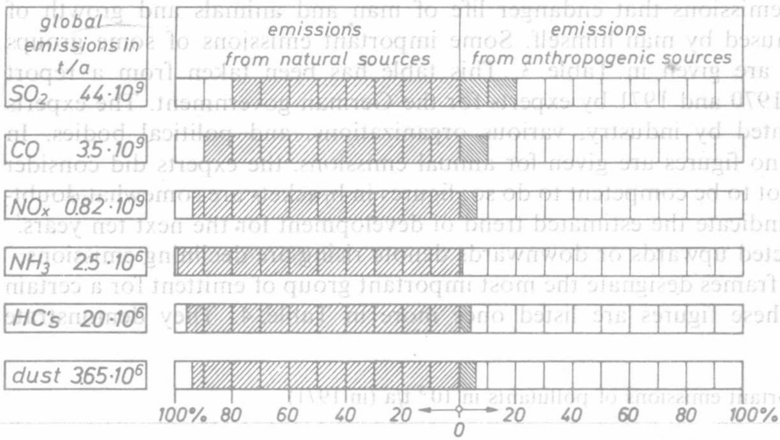

Fig. 8. Global emissions from natural and anthropogenic sources

ences in emissions from natural and anthropogenic sources and their relative importance can best be explained by the following equation:

$$\dot{M}_E = \dot{m}_E A_E \qquad (1)$$

$\dot{M}_E$ [kg/s] is the mass flow rate of the emitted pollutant, $\dot{m}_E$ [kg/m^2] is the specific mass flow rate, that is the mass flow rate per unit emission area of the emitted pollutant, and A_E is the emission area. Natural emissions are in most cases characterized by very small specific mass flow rates of the pollutants and by very large emission areas. A typical example for this case is the decomposition of organic matter that leads to emission of hydrocarbons, sulfur dioxide etc. An exception are volcanic emissions. In this case, there is a very large specific emission rate and a rather small emission area. But even for this condition, the emission is in general without much concern because pollutant emission is relatively seldom, and when it occurs, it takes place at a considerable height.

The volcano Aetna in Sicily emits an estimated amount of 1 million tons of sulfur dioxide per year, that is about half of the amount emitted in the Ruhr area, one of the highly industrialized parts of the Federal Republic of Germany. While the SO_2 emitted in the Ruhr area is of grave concern to the environment, the Aetna emissions play no serious role in air pollution, because the pollutants are emitted at a height of 3,263 meters. Emissions at this height are diluted to such an extent that they cause no harm. Anthropogenic emissions however are in many cases characterized by rather large specific pollutant flow rates and by very small emission areas.

Typical sources of anthropogenic emissions are chimneys. Chimneys of industrial plants are in general rather high so that emissions from these sources are not very important for the pollution of the biosphere close to the surface of the earth. In the domestic sector, however, the chimneys of household fire stations have a rather low height. The emission from these sources play a decisive role in the pollution of living quarters.