A Course in

AIR POLLUTION FOR ENGINEERS

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IN THE PAST TWO DECADES the need for environmental awareness has increased the enrollment of chemical engineers in environmental courses, especially in air pollution courses. This is true both for formal university courses and for the continuing education short courses.

Traditionally, most of the air pollution courses have been developed in civil and environmental engineering departments. Only a small percentage of chemical engineering departments offer a course related to air pollution. In 1978, there were 581 air pollution courses offered in 130 American and Canadian Universities and Colleges in 189 academic departments [1]. These departments varied from traditional engineering to disciplines like geography and biology, with only 27 chemical engineering departments offering an air pollution course.

The diversity of the disciplines in which the air pollution courses have been developed and the variations in the background of students have made the air pollution courses very non-uniform. Departments with multiple air pollution courses cover different aspects of the air pollution under one or more of the following topics: fundamentals of air pollution, atmospheric sampling and analysis, atmospheric chemistry and meteorology, modeling of atmospheric dispersions, aerosol science and technology, industrial pollution processes, theory and design of air pollution control systems, and air quality management. These courses have varied from very introductory and descriptive to strongly theoretical, with intensive use of mathematics, to highly application and design oriented ones.

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Many engineering students who do not intend to specialize in air pollution cannot afford to take several courses in air pollution. They would usually prefer to take one general course that would give them an overall understanding of the field. Several schools also offer a general air pollution course as an elective to students of different disciplines. Obviously, in this general air pollution course many of the above mentioned topics have to be selectively compressed or eliminated.

The air pollution course described in this article is specially designed to be a general course of one semester or two quarters duration, tailored to serve as an elective course for engineering students in their M.S. or senior level.

This course is different from other one-semester air pollution courses in several aspects. The order of presentation of the topics is completely new. The new arrangement is based on the principle of cause and effect. The theoretical basics are reviewed at the beginning of the course. Consequently, the subsequent topics are not presented as case studies, but as applications of the theoretical principles. Thus, the student studies and analyzes the applications with a creative approach and often can deduce the resultant phenomena before the empirical observations are presented. It is the main objective of this course to challenge the creative thinking of the students. This is achieved not only during the lectures, but also by the type of problems that are given during the quizzes and examinations. As a result of these efforts, the learning efficiency is improved and more material is covered in the course.

COURSE DESCRIPTION

The course consists of two major parts: fundamentals of air pollution, and control technology and equipment design. In the first part, the air pollution system is treated as a huge chemical reactor, where man is a moving boundary exposed to the pollutants. In the second part, the control technology is described and the design methods

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are discussed. Usually equal time is spent in teaching these two parts. However, in this article more space is devoted to the fundamentals of air pollution to show its special merits.

The most important reason for our study of air pollution is a concern both for our health and for that of future generations. The threat to our health may come from direct exposure to pollutants, or from indirect exposure through water, plants, animals, and generally from the entire environment.

The ecological effects of air pollutants depend on (a) the concentration of the pollutant, (b) the temperature, (c) the duration of exposure, and (d) the velocities of the surrounding air. In some cases other factors, such as concentrations of other constituents, may also interfere. Thus, in theory, in order to be able to evaluate the extent of the potential damage of air pollutants, one needs to know the concentration of every pollutant at any location and at any time.

The air surrounding the earth is considered as a huge non-homogeneous, non-uniform, and non-ideal chemical reactor which has an approximate shape of a spherical shell. In order to understand this non-ideal reactor, one needs to consider the following:

- **Chemical and physical constituents of the reactor and their properties**
- **Heat transfer and temperature distributions**
- **Fluid dynamics and velocity distributions**
- **Physical boundaries of the reactor and transport phenomena through these boundaries**
- **Interactive and combined phenomena of all these factors**

Chemical constituents of the atmosphere include not only nitrogen and oxygen but all reactive and non-reactive gases as well as the suspended particles in the atmosphere. Physical constituents are considered as atmospheric electricity, radioactivity and electromagnetic radiation; where solar radiation plays the major role. Therefore the course starts with a review of different pollutants of the atmosphere and electromagnetic radiation. This is followed by a study of the interaction of radiation with gaseous molecules, the principles of photochemistry, the formation and dynamics of aerosol particles, and the interaction of particles with electromagnetic radiation, electricity and radioactivity. It is at this stage that the students are introduced to the concept of free molecular and continuum flow behavior of particles. They learn about Brownian motion and phoretic forces and develop a general understanding of the significance of each phenomena under different conditions. The students also learn the role of wavelength in the absorption

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of electromagnetic radiation by chemical constituents and its significance in the initiation of different types of chemical reactions.

Before the discussion of atmospheric fluid dynamics, i.e., meteorology, the atmospheric energy balance is discussed. By introducing atmospheric layers and their role in filtering different wavelengths from solar radiation, the heat balance around the earth is introduced. The role of different chemical constituents in the atmospheric heat balance is discussed and the greenhouse effect is explained.

The fluid dynamics of the atmosphere as classified under macro-, meso- and micro-meteorology is introduced with emphasis on the concept of cause and effect, indicating the role of solar radiation and the atmospheric heat balance in the development of atmospheric motions. This discussion is further expanded to the vertical temperature distribution, lapse rate, inversion layers, and atmospheric stability.

Sources of pollution as inputs through the lower boundary of the reactor, i.e., the surface of

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earth, are reviewed and an account is given to emission inventories. At this stage atmospheric chemistry and different types of smogs are presented. A study of air pollution sinks, both through the lower boundary to the earth and through the tropopause to the upper levels of the atmosphere illustrates how pollutants are eliminated from the air. Water bodies, open lands, plants and lungs of living creatures are considered as some of the sinks on the surface of the earth, while stratospheric ozone layer is a sink at the upper levels of the atmosphere.

To account for localized variations of pollution, dispersion of pollutants in the atmosphere from point, line, and surface sources are presented and the concept of atmospheric modeling is introduced.

Throughout the presentation of this global reactor model, the principles of global material and energy balances are repeatedly emphasized so that the students realize that whatever pollution is emitted to the atmosphere, eventually is going to be removed in the sinks in the boundaries of the reactor.

At this stage, the student, in principle, is capable of predicting the fate of and concentrations of atmospheric pollutants. The effects of air pollutants on the atmospheric environment are discussed by presenting such topics as ozone layer depletion, acid rain, and visibility reduction. Air pollution damage to vegetation and materials is followed by the effects on human and animal health.

The student at this time is quite familiar with the behavior of different gaseous and particulate pollutants and therefore the analysis of their effects is no longer a case study. For example, the dependency of particle capture rate on the particle size in the lungs is not a matter to be accepted and memorized. The student recognizes the relative significance of interception, sedimentation and diffusion, so he or she can deduce the concept of lung deposition.

Once the effects of air pollutants are studied, the safe limits of pollutants and the existing uncertainties in these limits are discussed. Air pollution regulations are presented under the two classes of receptor and emittor standards. A brief summary of air pollution measuring techniques completes the section on the fundamentals of air pollution.

In the second half of the course, control technology is taught. Again the ground is laid by reviewing the basic chemical engineering principles to show the thermodynamic and rate limitations on the formation of pollutants. Material balances are used to calculate the emission rates. An energy balance is used to calculate the combustion and outlet stream temperature. Chemical equilibria show the thermodynamic limitations on the formation of pollutants. Finally, chemical kinetics explain the rate phenomena and the time factor involved in the formation of pollutants. This review is usually repetitious to chemical engineers, but it is required for the understanding of the rest of the discussion. Therefore, it must be taught if non-chemical engineers are present in the class.

At this stage, emission inventories and emission factors are briefly reviewed. Incineration is discussed as the first control technology. As another application of the basic principles, automobile emission control is presented. Again the discussion is based on thermodynamic and kinetic principles; therefore the student can deduce the outcome of most of the control techniques.

Control of gaseous emissions by absorption and adsorption and the sizing of equipment are discussed. The students are continuously reminded of the economic limitations of gas cleaning processes so that they realize that, even with the best available control technology, the exhaust stream will contain some low levels of pollutants which need to be properly disposed into the atmosphere. The stack as a means of this dispersion of pollutants is described and its design methods are exercised. However, it is also emphasized that "dilution is *not* a solution to pollution" and whatever is released into the atmosphere will eventually return to the earth in some form.

A theoretical discussion of the aerodynamic capture of particles and the forces responsible for the collection and separation of particles precedes the particulate control section.

Particulate control equipment is divided into two groups; the equipment in which a specific body force results in the separation of the particles from the carrier gas, and the equipment which operates on the basis of the aerodynamic capture of particles by an object or obstacle. In the first class, settling chambers, centrifugal separators and cyclones, and electrostatic precipitators are discussed. In the second class, filtration and wet scrubbing are described. For every type of equipment, the operating principles and the physical construction are presented first, followed by design principles and equations. Emphasis is placed on sizing of equipment, calculation of collection efficiencies, and pressure drops.

The final part of the course is based on comparing particulate control equipment. The criteria for the selection of suitable equipment is presented and the guidelines to achieve an economical design are discussed. At present, there seems to be a need for the coverage of flue gas desulfurization and other special topics, but due to time limitations these have not been incorporated in the course. Table 1 gives a more detailed course outline.

TABLE 1 Course Outline

- I—Fundamentals of Air Pollution
  - Introduction to air pollution
    - Atmosphere, a huge chemical reactor
  - Chemical Constituents of the Atmosphere
    - Gaseous pollutants
    - Particulates
  - Physical Constituents of the Atmosphere
    - Electromagnetic radiation, solar radiation
    - Radioactivity, ions and atmospheric electricity
  - Interaction of Radiation with Gases
    - Absorption and emission of radiation by gaseous molecules
    - Photoionization and photoexcitation of gases
    - Principles of photochemistry
  - Aerosol Particles
    - Formation of particles by homogeneous and heterogeneous nucleations
    - Growth of particles by coagulation
    - Knudsen number and regimes of particle dynamics
    - Brownian motion and phoretic forces
  - Interaction of Radiation with Particles
    - Optical properties of particles: Mie scattering and Rayleigh scattering
  - Atmospheric Heat Balance
    - Radiative heat transfer
    - Atmospheric layers and solar radiation
    - Energy balance of the earth
    - Greenhouse effects
  - Atmospheric Fluid Dynamics
    - Macrometeorology and general circulation
    - Cyclones and anticyclones
    - Planetary boundary layer and wind profiles
    - Temperature profiles and lapse rate
    - Verticle motions in the atmosphere
    - Atmospheric stability and inversions
  - Sources of Air Pollution
    - Natural and anthropogenic sources
    - Emission inventories
  - Atmospheric Chemistry
    - Photochemical smog
    - Sulfurous smog
    - Miscellaneous atmospheric reactions
  - Sinks of Atmospheric Pollution
    - Sinks at the earth's surface: water bodies, earth, vegetation, animals
    - Sinks at the upper layers of the atmosphere
  - Atmospheric Dispersion
    - Gaussian plume and ground concentrations
    - Dispersion of particulates and their deposition from plumes
    - Dispersion from line and area sources
    - Modeling of atmospheric dispersion by unicell and multicell techniques
  - Effects of Air Pollution
    - Global atmospheric effects: ozone depletion
    - Regional atmospheric effects: acid rain
    - Localized atmospheric effects: visibility reduction
    - Effects on vegetation
    - Effects on material
    - Effects on human health
      - Direct and indirect exposure
      - Lung and its defense mechanisms
    - Effects of gaseous and particulate pollutants on the respiratory system
    - Other effects of pollutants on health
  - Air Pollution Regulations
  - Sampling and Analysis of Air Pollutants
  - Management of Air Pollution
- II—Control Technology and Design
  - Basic Principles
    - Material balance
    - Energy balance
    - Chemical equilibria
    - Reaction rates
  - Emission Inventories and Emission Factors
  - Incineration
  - Automobile Emissions and Control
    - Fuel tank, carburator and crankcase emissions
    - Exhaust gas emissions and its control
  - Absorption
  - Adsorption
  - Dispersion of Pollutants From Stacks, Stack Height
  - Particle Size Distributions
  - Collection Efficiencies and Penetrations
  - Grade Efficiencies and Overall Efficiencies
  - Aerodynamic Separation and Capture of Particles
    - Gravity, centrifugal and electrostatic forces
    - Calculation of particle trajectories and stop distances
    - Capture of particles by obstacles: impaction, interception, diffusion and seiving
  - Particulate Control Equipment and Their Design
    - Settling chambers
    - Centrifugal separators, cyclones
    - Electrostatic Precipitators
    - Filtration, fabric filters
    - Wet scrubbing
    - Economics and comparative design of particulate control equipment

TEXTBOOK

In the past two decades several textbooks have been written for air pollution courses. Unfortunately, none of them can be used for the entire course. Some of these textbooks cover primarily the fundamentals [2-6], while others cover the control aspects [7-10]. The textbooks that attempt to cover both the fundamentals and control [11, 12] do not place the desired emphasis on different topics. In addition, the sequence of topics in the textbooks is significantly different from the sequence of this course. Therefore no single textbook was found suitable for this course. For every topic, appropriate pages from different sources are recommended for reading.

ASSIGNMENTS AND EXAMINATIONS

Two types of assignments are normally given. Computational homework problems, through which the students learn to use the basic design equations, are assigned on a regular weekly basis. During the first few weeks, while the fundamentals are being covered, not many computational problems can be given. Therefore, certain reading materials are assigned which are later tested by short quizzes. In order to minimize the memorization aspect of these assignments and improve the creativity and critical thinking of the students, no direct questions are asked on the assigned reading material. The questions are indirect and require some creative thinking based on the studied material. Three one-hour exams and one final exam are given during the semester. These examinations are composed of questions similar to the ones in the short quizzes and computational problems. Since no direct questions are asked, all the examinations and short quizzes are handled on an open-book open-notes basis.

SUMMARY AND CONCLUSIONS

The described air pollution course which covers both the fundamentals and control of air pollution introduces a new sequential structure for its topic presentation. This new structure is built on the basis of theoretical principles and has minimized the traditional case study approach. The major objective throughout the course is to prepare the students to become creative thinkers capable of analyzing existing and future/new air pollution problems.

This course, developed and taught at Oklahoma State University, has attracted many superior students from different engineering disciplines. It has successfully challenged the students and has maintained their interest and enthusiasm throughout the courses. □

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