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Air Pollution

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Najib Nicolas Gerges, Ph.D., P.E.

CED CANADA
engineering.ca
CPD FOR THE PROFESSIONAL

Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.ca

www.cedengineering.ca

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CHAPTER 1: INTRODUCTION TO AIR POLLUTION

1. Introduction: Why Air Pollution Is an Engineering Problem.

Air pollution has long been associated with environmental degradation and public health concerns; however, its causes, behavior, and solutions are fundamentally rooted in engineering science. The generation, transport, transformation, and removal of air pollutants are governed by physical laws, chemical reactions, and system constraints that can be quantified and analyzed. As a result, air pollution must be understood not only as a social or regulatory issue, but as a technical challenge requiring engineering analysis, modeling, and design. As illustrated in Figure 1, air pollution can be analyzed as a system in which emissions, transport, transformation, and removal processes interact to determine ambient pollutant concentrations.

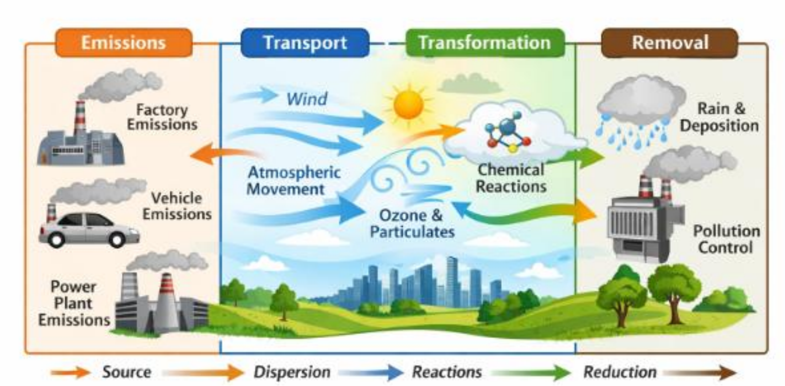


Figure 1: Air Pollution as an Engineering System

Air pollution refers to the presence of solid particles, liquid droplets, or gaseous compounds in the atmosphere at concentrations that result in adverse effects on human health, ecological systems, materials, or climate processes. From an engineering perspective, the atmosphere is treated as a dynamic system in which pollutants are emitted from sources at measurable rates, transported by atmospheric motion, transformed through chemical and physical processes, and removed through natural or engineered mechanisms.

Engineering analysis of air pollution therefore involves understanding emission sources, transport phenomena governed by fluid mechanics, chemical transformations controlled by reaction kinetics, and removal processes such as deposition or treatment. Effective control strategies rely on engineering principles drawn from fluid mechanics, thermodynamics, mass transfer, atmospheric chemistry, systems modeling, and regulatory analysis. Engineers play a central role in predicting pollutant behavior, designing control technologies, and ensuring compliance with air quality standards.

2. Fundamental Definition of Air Pollution.

A clear and consistent definition of air pollution is essential for analysis, regulation, and control. Engineers must be able to distinguish between naturally occurring atmospheric constituents and pollutants that pose risks to health or the environment. This distinction provides the foundation for air quality modeling, standard setting, and engineering decision-making.

A substance is classified as an air pollutant when three conditions are met: it is present in the atmosphere, its concentration exceeds natural background levels, and it causes, or has the potential to cause harm to humans, ecosystems, materials, or climate systems. These criteria emphasize that pollution is defined not merely by presence, but by concentration, exposure, and impact. A conceptual relationship between pollutant concentration, background levels, regulatory thresholds, and resulting health or environmental impacts is illustrated in Figure 2.

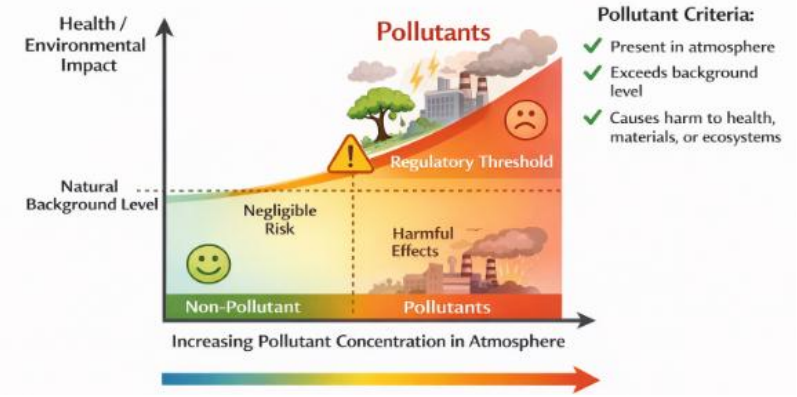


Figure 2: Defining Air Pollutants Based on Concentration and Impact

Air pollution problems are commonly formulated using mass balance principles. In its general form, the mass balance states that the rate of accumulation of a pollutant within a defined system equals the difference between inputs and outputs, adjusted for internal generation and removal processes:

Accumulation = Input − Output + Generation – Removal

Figure 3 represents a conceptual mass balance showing pollutant input, output, generation, removal, and accumulation within an atmospheric control volume.

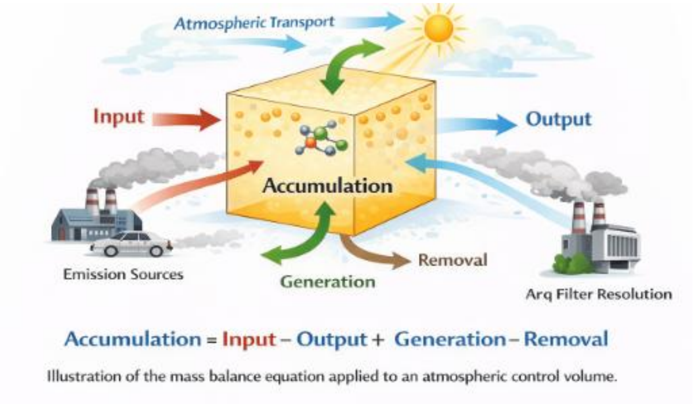


Figure 3: Mass Balance on an Atmospheric Control Volume

This relationship forms the analytical basis for a wide range of engineering applications, including indoor air quality assessment, urban pollution modeling, and atmospheric dispersion analysis. Nearly all air quality models used in practice are extensions or approximations of this fundamental principle.

3. Classification of Air Pollutants.

Air pollutants are classified to simplify analysis, guide regulatory frameworks, and inform control strategy selection. One of the most important distinctions is whether a pollutant is emitted directly or formed through reactions in the atmosphere. This classification has significant implications for monitoring, modeling, and control.

3.1 Primary Pollutants

Primary pollutants are released directly into the atmosphere from identifiable sources. Their ambient concentrations are closely linked to emission rates, operating conditions, and fuel or process characteristics. Because the source–pollutant relationship is relatively direct, primary pollutants are often the initial focus of engineering control efforts.

Common primary pollutants include carbon monoxide produced by incomplete combustion, sulfur dioxide from sulfur-containing fuels, nitrogen oxides formed during high-temperature combustion, particulate matter generated by combustion and mechanical processes, and volatile organic compounds released through fuel evaporation and solvent use.

Primary pollutants are generally easier to manage because their sources can be located and quantified, emissions can be measured at exhaust points or stacks, and established control technologies, such as scrubbers, filters, or catalytic systems, can be applied directly to the emission stream.

3.2 Secondary Pollutants

Secondary pollutants are not emitted in their final form. Instead, they are produced in the atmosphere through chemical reactions involving primary pollutants and naturally occurring atmospheric constituents. These reactions are often driven by sunlight and influenced by temperature, humidity, and atmospheric mixing conditions.

Examples of secondary pollutants include ozone formed through reactions between nitrogen oxides and volatile organic compounds, secondary particulate matter such as sulfates and nitrates, photochemical smog, and compounds such as peroxyacetyl nitrate. Unlike primary pollutants, secondary pollutants may reach their highest concentrations far from their original emission sources.

Controlling secondary pollutants is particularly challenging because their formation depends on complex, nonlinear interactions among multiple precursor species, meteorology, and radiation. As a result, reducing emissions of a single precursor does not always lead to proportional reductions in pollutant concentrations.

4. Spatial and Temporal Scales of Air Pollution.

Air pollution does not occur uniformly across space or time. Pollutant concentrations vary depending on the scale of interest, ranging from localized emission plumes to global atmospheric changes. Understanding these scales is essential for selecting appropriate modeling approaches and control strategies.

From a spatial perspective, pollution may occur at the local scale near roadways or industrial facilities, at the urban or regional scale where smog and acid deposition develop, or at the global scale where pollutants influence climate and stratospheric chemistry. Each scale involves different dominant transport mechanisms and governing processes.

Temporal scales are equally important. Pollutant behavior may be analyzed over seconds or minutes to study plume dispersion, over hours or days to assess smog formation, or over decades to evaluate long-term climate impacts. Engineering models must therefore be matched carefully to both the spatial and temporal scale of the problem.

5. Units of Air Pollutant Concentration.

Accurate quantification of pollutant concentrations is a fundamental requirement in air pollution engineering. Measurements, standards, and model outputs may be expressed in different units, making unit conversion a routine but critical task. Errors in unit conversion can lead to incorrect conclusions regarding air quality and regulatory compliance.

5.1 Common Units

Air pollutant concentrations are commonly reported using either volumetric or mass-based units. Volumetric units include parts per million (ppm) and parts per billion (ppb), which express the ratio of pollutant molecules to air molecules. Mass-based units, such as micrograms per cubic meter (µg/m³), express the mass of pollutant per unit volume of air.

Regulatory standards are frequently stated in mass-based units, while field measurements and instrument outputs may be reported in volumetric terms. Engineers must therefore be proficient in converting between these units.

5.2 Conversion Formula

Under standard conditions of 25°C and 1 atmosphere, the conversion between ppm and µg/m³ for gaseous pollutants is given by:

$$C(\mu g/m^3) = ppm \times \frac{MW \times 10^6}{24.45}$$

where *MW* is the molecular weight of the pollutant in grams per mole, and 24.45 represents the molar volume of an ideal gas in liters per mole at standard conditions.

Example 1: Concentration Conversion (ppm → µg/m³)

Convert 0.10 ppm of SO_2 to µg/m³ at standard conditions.

Given:

- $MW(SO_2) = 64$ g/mol

Solution:

$$C = 0.10 \times \frac{64 \times 10^6}{24.45}$$
$$C = 262\ \mu g/m^3$$

Interpretation:
This concentration is typical of heavily polluted industrial zones.

Example 2: Regulatory Compliance Evaluation

If the 24-hour air quality standard for SO_2 in example 1 is 125 µg/m³, what do you conclude?.

Decision:

$$262 > 125 \Rightarrow \text{Non-compliant}$$

Engineering implication:
Emission reduction or process modification is required.

Example 3: Reverse Conversion (μg/m³ → ppm)

Convert 50 μg/m³ of CO to ppm.

Given:

- MW(CO) = 28 g/mol

$$ppm = \frac{C \times 24.45}{MW \times 10^6}$$

$$ppm = \frac{50 \times 24.45}{28 \times 10^6} = 0.044\ ppm$$

Example 4:

Convert 0.03 ppm of NO_2 (MW = 46) to μg/m³.

$$C = 0.03 \times \frac{46 \times 10^6}{24.45} = 56.4\ \mu g/m^3$$

Example 5:

Identify the pollutant type:

- CO → Primary
- O_3 → Secondary

Example 6:

Explain why secondary pollutants are harder to control.

Answer:
Their formation depends on atmospheric chemistry, meteorology, and sunlight, not just emission rates.

6. Common Engineering Errors.

Common mistakes in air pollution analysis include:

- Confusing ppm with µg/m³.
- Ignoring temperature and pressure effects.
- Comparing concentrations with different averaging times.
- Assuming emission reductions directly reduce secondary pollutant concentrations.

Recognizing and avoiding these errors is essential for producing defensible engineering analyses and reliable regulatory submissions.

CHAPTER 2: ATMOSPHERIC COMPOSITION & METEOROLOGY

1. Role of Meteorology in Air Pollution Engineering.

Air pollutant concentrations observed at ground level are not determined solely by emission rates. In many cases, identical emissions can produce vastly different air quality outcomes depending on prevailing atmospheric conditions. For this reason, meteorology is a central component of air pollution engineering and must be considered alongside source characteristics and control technologies. Figure 4 illustrates how identical emissions from a source can lead to vastly different ground-level pollutant concentrations depending on meteorological conditions. Under weak winds and a stable atmosphere, pollutants accumulate near the source, producing high concentrations. Under stronger winds and unstable conditions, vertical and horizontal mixing increase, resulting in wider dispersion and lower ground-level concentrations. The figure emphasizes the central role of wind speed, atmospheric stability, and mixing in air pollution engineering.

Figure 4: Influence of Meteorology on Pollutant Dispersion

Meteorological conditions govern how pollutants move, spread, react, and persist in the atmosphere. Wind speed and direction determine horizontal transport, while temperature structure and atmospheric turbulence control vertical mixing and dilution. Atmospheric conditions also influence chemical reaction rates, pollutant lifetimes, and the effectiveness of natural removal processes such as deposition and scavenging.

From an engineering perspective, unfavorable meteorological conditions, such as weak winds, strong atmospheric stability, or shallow mixing depths, can produce severe pollution episodes even when emissions are relatively modest. Conversely, strong winds and vigorous mixing can maintain acceptable air quality despite high emission rates. Understanding these relationships is essential for dispersion modeling, regulatory compliance analysis, and the design of effective air quality management strategies.

2. Vertical Structure of the Atmosphere.

The atmosphere is vertically stratified into layers based on how temperature changes with altitude. These layers differ in physical behavior, mixing characteristics, and relevance to air pollution problems. Engineers consider atmospheric layering to determine how pollutants disperse, whether they are confined near the surface, and how long they may remain in the atmosphere.

2.1 Troposphere

The troposphere extends from the Earth's surface to an altitude of approximately 10 to 12 kilometers, depending on latitude and season. This layer contains roughly three-quarters of the total atmospheric mass and is the region in which all weather phenomena occur.

For air pollution engineering, the troposphere is of primary importance. Nearly all anthropogenic emissions are released within this layer, and most pollutant transport, transformation, and human exposure occur here. Temperature in the troposphere generally decreases with altitude, a condition that promotes vertical motion and atmospheric mixing under favorable conditions. Variations in this temperature structure directly affect pollutant dispersion and accumulation.

2.2 Stratosphere

The stratosphere lies above the troposphere and is characterized by an increase in temperature with height due to absorption of ultraviolet radiation by ozone. Vertical mixing in this layer is limited, and pollutants introduced into the stratosphere tend to remain there for long periods.

While stratospheric processes are critical for global-scale phenomena such as ozone depletion and climate change, they are of limited relevance to most local and regional air pollution engineering problems. Consequently, engineering analyses focused on ground-level air quality typically emphasize tropospheric behavior.

A vertical structure of the atmosphere is illustrated in Figure 5.

Figure 5: Vertical Structure of the Atmosphere

3. Atmospheric Pressure, Density, and Temperature.

Basic thermodynamic properties of air, pressure, density, and temperature, play a fundamental role in atmospheric motion and pollutant behavior. These properties influence buoyancy forces, plume rise, atmospheric stability, and the effectiveness of vertical mixing. Engineers routinely apply gas laws to quantify these relationships in dispersion and plume rise calculations.

3.1 Ideal Gas Law Applied to Air

Under most environmental conditions, air can be accurately modeled as an ideal gas. The ideal gas law relates pressure, volume, temperature, and mass and provides a convenient framework for atmospheric calculations:

$$PV = nRT$$

When expressed in terms of density, the relationship becomes:

$$\rho = \frac{P}{RT}$$

where ρ is air density, P is atmospheric pressure, R is the specific gas constant for air, and T is absolute temperature. Variations in air density influence buoyancy-driven motion, plume behavior, and dispersion rates.

Example 1: Air Density at Standard Conditions

Calculate the air density at 20°C and 1 atm.

Given:

- $P = 101325\text{Pa}$
- $T = 293\text{K}$

Solution:

$$\rho = \frac{101325}{287 \times 293}$$

$$\rho = 1.20\ \text{kg/m}^3$$

Engineering interpretation:

This value is commonly used in dispersion and plume rise calculations.

Example 2: Effect of Temperature on Density

Calculate air density at 0°C (273 K).

$$\rho = \frac{101325}{287 \times 273} = 1.29\ \text{kg/m}^3$$

Conclusion:
Colder air is denser, increasing stability and reducing vertical mixing.

4. Wind Speed and Wind Direction.

Wind is the primary mechanism responsible for the horizontal transport of air pollutants. Without wind, emissions would accumulate near their sources, leading to extreme local concentrations. Engineers therefore rely heavily on wind measurements when evaluating pollutant transport, exposure, and compliance with air quality standards.

4.1 Wind as a Transport Mechanism

Wind speed directly affects how rapidly pollutants are carried away from emission sources. Higher wind speeds generally enhance dilution and reduce ground-level concentrations near sources, while low wind speeds allow pollutants to accumulate. Many severe air pollution episodes are associated with periods of calm or weak winds.

4.2 Wind Profiles

Wind speed typically increases with height above the ground due to reduced surface friction. Near the surface, wind is strongly influenced by terrain roughness, buildings, and vegetation. For consistency in monitoring and modeling, wind measurements are commonly reported at a height of 10 meters, with adjustments applied when estimating conditions at stack height or plume elevation.

Example 3: Travel Time of Pollutant Plume

A pollutant plume travels with a wind speed of 3 m/s. How long does it take to reach a receptor 2 km downwind?

$$t = \frac{2000}{3} = 667\ \mathrm{s} = 11.1\ \mathrm{min}$$

5. Atmospheric Stability and Temperature Gradients.

Atmospheric stability describes the tendency of the atmosphere to resist or enhance vertical motion. Stability conditions strongly influence pollutant dispersion and are therefore central to air pollution meteorology and engineering modeling.

5.1 Environmental Lapse Rate (ELR)

The environmental lapse rate is the actual rate at which ambient air temperature decreases with altitude at a given time and location. A typical average value is approximately 6.5°C per kilometer, although actual conditions vary widely depending on weather patterns and surface characteristics.

Figure 6 illustrates the temperature–altitude profiles for stable, neutral, and unstable atmospheres. The dashed line represents the dry adiabatic lapse rate. Stable conditions occur when the environmental lapse rate is less than the adiabatic rate, suppressing vertical motion. Neutral conditions produce moderate mixing when both rates are similar. Unstable conditions arise when the environmental lapse rate exceeds the adiabatic rate, enhancing vertical mixing and pollutant dispersion.

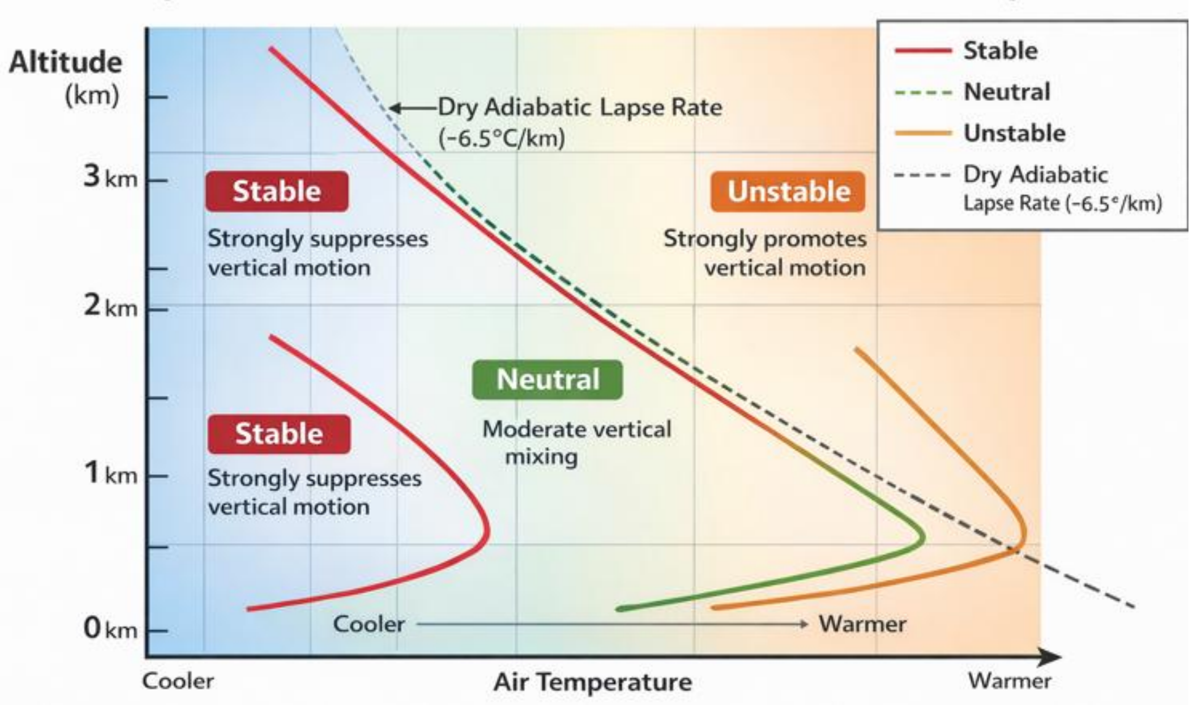


Figure 6: Stability Temperature Profiles

Stability is determined by comparing the environmental lapse rate with the rate at which an air parcel changes temperature as it moves vertically. Unstable conditions promote strong vertical mixing and low pollutant concentrations, while stable conditions suppress mixing and allow pollutants to accumulate near the ground. Neutral conditions produce moderate dispersion. Table 1 summarizes the stability conditions.

Table 1: Stability Conditions

Condition	Description	Pollution Effect
Unstable	Strong vertical mixing	Low concentrations
Neutral	Moderate mixing	Moderate concentrations
Stable	Weak mixing	High concentrations

6. Temperature Inversions.

Under certain meteorological conditions, the normal decrease of temperature with height is reversed, resulting in a temperature inversion. Inversions represent some of the most hazardous atmospheric conditions for air quality.

6.1 Definition

A temperature inversion occurs when air temperature increases with altitude, creating a stable atmospheric layer that inhibits vertical mixing. Common types include radiation inversions, subsidence inversions, and advection inversions. Inversions trap pollutants near the surface, often leading to rapid increases in concentration and exceedance of air quality standards.

Example 4: Inversion Identification

Given:

- Nighttime
- Clear skies
- Low wind speed (1–2 m/s)

Conclusion:
Radiation inversion → Very stable atmosphere

7. Pasquill–Gifford Stability Classes.

To standardize atmospheric stability assessment for dispersion modeling, conditions are classified using the Pasquill–Gifford system. This system categorizes stability from very unstable to very stable based on wind speed, solar radiation during the day, and cloud cover at night. These classes are widely used in regulatory dispersion models as presented in Table 2.

Table 2: Pasquill–Gifford Stability Classes

Class	Stability
A	Very unstable
B	Unstable
C	Slightly unstable
D	Neutral
E	Slightly stable
F	Very stable

Figure 7 illustrates typical plume shapes produced under different atmospheric stability conditions. Unstable atmospheres promote strong vertical mixing and looping plumes, resulting in rapid dilution. Neutral conditions produce coning plumes with moderate dispersion. Stable atmospheres suppress vertical motion, leading to fanning plumes and elevated ground-level concentrations. Lofting and fumigation cases associated with temperature inversions demonstrate how stratification can either reduce or intensify near-surface pollutant impacts.

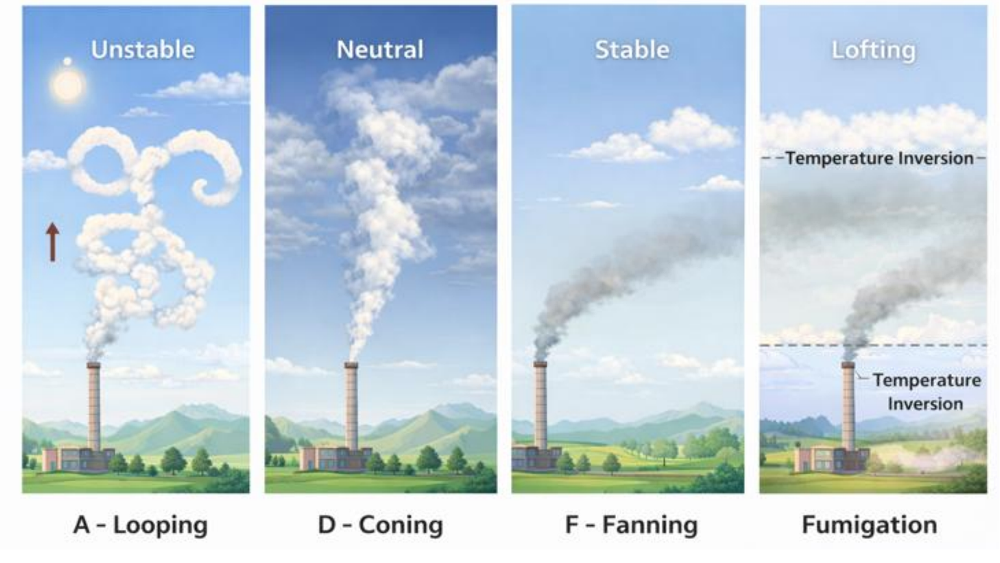


Figure 7: Influence of Atmospheric Stability on Pollutant Plume Dispersion

Example 5: Stability Classification

Determine the stability class for:

- Nighttime
- Clear sky
- Wind speed = 2 m/s

Answer:
Class F – Very stable

Nighttime conditions with clear skies and a wind speed of 2 m/s correspond to Class F, indicating very stable atmospheric conditions. This classification signals a high potential for pollutant accumulation.

8. Mixing Height and Its Importance.

The mixing height represents the vertical extent of the atmosphere within which pollutants can disperse. A shallow mixing height limits dilution and increases pollutant concentrations, while a deep mixing layer enhances dispersion and reduces exposure. Engineers use mixing height estimates to assess pollution potential and interpret monitoring data.

Figure 8 compares two scenarios: (a) a shallow mixing layer and (b) a deep mixing layer. In the shallow case, pollutants are confined to a smaller volume, resulting in higher ground-level concentrations and greater exposure risk. In the deep case, pollutants disperse into a larger volume, producing lower concentrations at the surface. This illustrates why low mixing heights during stable conditions often coincide with severe pollution episodes.

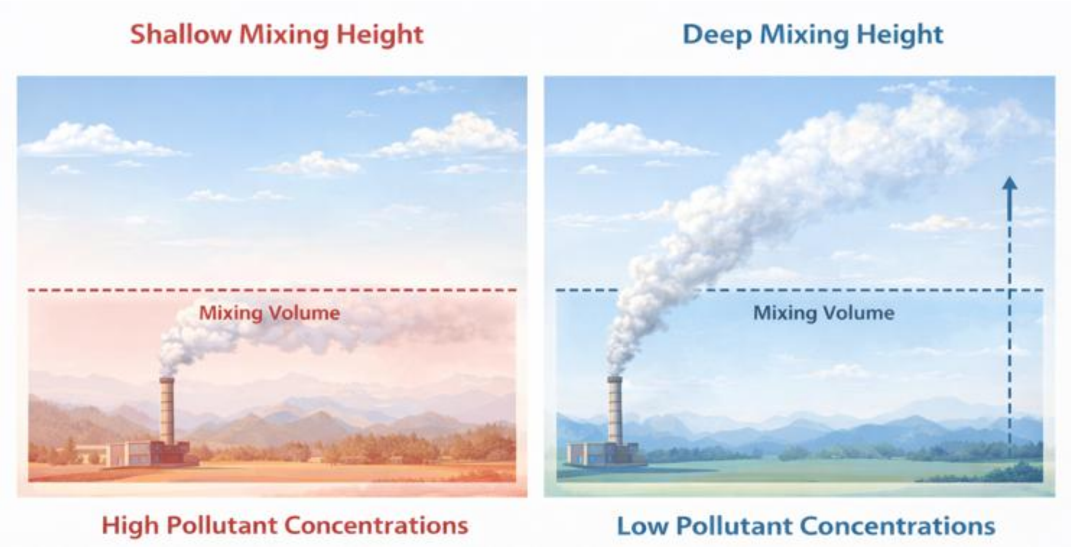


Figure 8: Effect of Mixing Height on Ground-Level Pollutant Concentrations

Given:

- Emissions = 200 kg/day
- Mixing height = 500 m
- City area = 100 km²

Volume:

The mixing volume is calculated assuming uniform mixing within a control volume:

$$V = A \times H$$

where:

- V = mixing volume (m^3)
- A = city area (m^2)
- H = mixing height (m)

$$V = 100 \times 10^6 \times 500 = 5 \times 10^{10}\ m^3$$

Average concentration estimate:

The average pollutant concentration is estimated using:

$$C = \frac{M}{V}$$

where:

- C = average concentration $\left(\mu\text{g/m}^3\right)$
- M = pollutant mass (μg)
- V = mixing volume (m^3)

$$C = \frac{200 \times 10^6}{5 \times 10^{10}} = 4\ \mu g/m^3$$

9. Engineering Implications for Air Quality Management.

Meteorological conditions influence nearly every aspect of air quality management. They affect emission permitting, stack height design, emergency response planning, and urban development decisions. Engineers must integrate meteorological data into dispersion models, permitting analyses, and control system design to ensure regulatory compliance, public safety, and robust performance under adverse conditions.

CHAPTER 3: AIR POLLUTANTS AND EMISSION SOURCES

1. Role of Pollutants and Sources in Air Pollution Engineering.

Effective air pollution analysis begins with a clear understanding of the substances being emitted and the activities responsible for their release. Engineers cannot model dispersion, evaluate health impacts, or design control systems without first identifying the nature of the pollutants and the sources from which they originate. This foundational step establishes the technical basis for all subsequent air quality assessments.

Understanding pollutants and sources allows engineers to:

- Identify the type of pollutant.
- Characterize its physical and chemical properties.
- Determine the source category.
- Quantify emission rates.

Different pollutants behave very differently in the atmosphere. Gases disperse and react chemically, while particulate matter can settle, agglomerate, or penetrate deeply into the human respiratory system. Engineering decisions depend critically on these behaviors.

In air pollution engineering, pollutants are defined as substances whose presence in the ambient atmosphere can cause health, ecological, or visibility impacts, or contribute to climate forcing.

2. Major Air Pollutants of Engineering Concern.

Air pollution engineering focuses on pollutants with significant environmental and health impacts. These pollutants are common in urban and industrial environments and are the primary targets of monitoring, regulation, and control. Understanding their sources and effects is essential for engineering analysis and decision-making.

2.1 Criteria Pollutants

Criteria pollutants are a group of air contaminants for which ambient air quality standards have been established due to their prevalence and documented health impacts as presented in Table 3. These pollutants are routinely monitored and regulated, making them central to air quality management and engineering practice.

Table 3: Criteria Pollutants

Pollutant	Primary Sources	Type	Key Health Effects	Control Notes
CO	Vehicles, combustion.	Primary	Oxygen deprivation	Catalytic converters, combustion efficiency.
SO_2	Power plants, refineries.	Primary	Respiratory irritation	Scrubbers, low-sulfur fuels.
NO_x	Engines, boilers.	Primary	Ozone formation	Selective catalytic reduction, low-NO_x burners.
PM_{10}	Dust, industry.	Primary	Respiratory effects	Cyclones, filters.
$PM_{2.5}$	Combustion.	Primary/Secondary	Cardiovascular disease	Baghouses, wet scrubbers.
O_3	NO_x + VOCs	Secondary	Lung damage	Reduce precursors (NO_x, VOCs)
Pb	Smelting, batteries.	Primary	Neurological damage	Source substitution, filtration.

2.2 Particulate Matter (PM)

Particulate matter represents one of the most complex and harmful categories of air pollutants. Its impact depends strongly on particle size, which influences atmospheric behavior, transport distance, and the depth of penetration into the human respiratory system. Engineers classify particulate matter based on aerodynamic diameter to assess these effects.

Particulate matter is classified by aerodynamic diameter:

- PM_{10}: particles $\leq 10\ \mu m$
- $PM_{2.5}$: particles $\leq 2.5\ \mu m$

Smaller particles:

- Remain suspended longer.
- Penetrate deeper into lungs.
- Pose greater health risks.

Particles $< 1\ \mu m$ (PM_1 and ultrafine) are particularly important for health because they penetrate into the bloodstream.

Example 1: Particle Settling Insight

Explain why $PM_{2.5}$ remains airborne longer than PM_{10}.

Answer:
Smaller particles have lower settling velocities, making gravitational removal less effective.

2.3 Secondary Pollutants

Secondary pollutants are formed in the atmosphere through chemical reactions involving primary pollutants and natural constituents. These reactions are influenced by sunlight, temperature, humidity, and atmospheric mixing. Secondary pollutants form in the atmosphere from precursors, while secondary particulate matter forms through gas-to-particle conversion of precursors such as SO_2 and NO_x.

Examples:

- Ozone (O_3) formed from NO_x + VOCs.
- Secondary particulate matter: sulfates, nitrates.
- Photochemical smog, peroxyacetyl nitrate (PAN).

Engineering challenge: Reducing a single precursor does not always proportionally reduce secondary pollutant concentrations due to complex, nonlinear chemistry.

A schematic of secondary formation is illustrated in Figure 9.

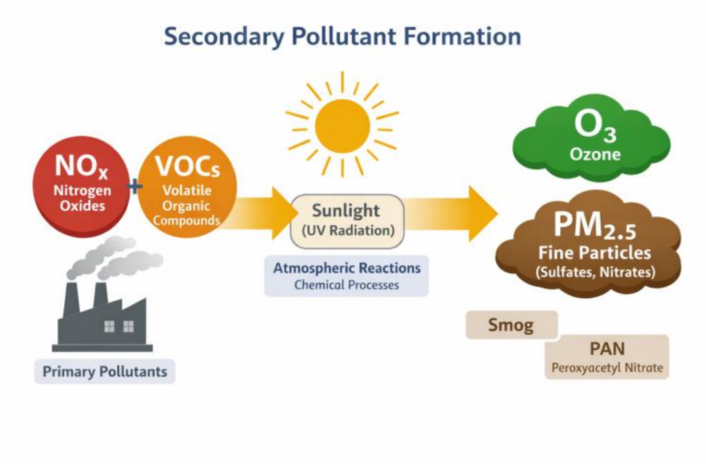


Figure 9: Secondary Pollutant Formation

3. Classification of Emission Sources

Air pollution sources are categorized based on their physical configuration and emission characteristics. This classification is critical for selecting appropriate modeling approaches, monitoring strategies, and regulatory controls. Different source types present different engineering challenges.

3.1 Point Sources

Point sources are emissions that originate from a single, clearly defined location. These sources are typically associated with industrial processes and energy production facilities, making them relatively straightforward to identify and regulate. Point sources emit pollutants from a single, identifiable location, usually through a stack.

Examples:

- Power plants.
- Industrial boilers.
- Incinerators.

Characteristics:

- High emission rates.
- Easier to regulate and control.
- Suitable for stack-based modeling.

3.2 Line Sources

Line sources represent emissions distributed along a linear path rather than concentrated at a single point. These sources are particularly important in transportation-related air pollution and require specialized modeling techniques.

Line sources emit pollutants along a linear path.

Examples:

- Highways.
- Railways.
- Airport runways.

Engineering challenge:

- Emissions vary spatially.
- Difficult to model as a single point.

3.3 Area Sources

Area sources consist of numerous small emission points spread over a wide region. While individual sources may emit small quantities of pollutants, their combined impact can be substantial, especially in urban environments.

Area sources consist of many small, distributed emitters.

Examples:

- Residential heating.
- Urban areas.
- Agricultural fields.

Often difficult to control individually but significant collectively.

4. Emission Rate and Emission Factor Concepts

Quantifying emissions is a core task in air pollution engineering. Engineers rely on emission rates and emission factors to translate real-world activities into measurable pollutant releases that can be used in models and inventories.

4.1 Emission Rate

The emission rate expresses how much pollutant is released over a given period of time. It is a fundamental input for dispersion modeling, exposure assessment, and regulatory reporting.

Emission rate (E) is the mass of pollutant released per unit time.

E = Mass emitted / Time

Units:

- g/s
- kg/day
- tons/year

4.2 Emission Factors

Emission factors provide a practical method for estimating emissions when direct measurement is not feasible. They relate emissions to an activity level such as fuel consumption, production output, or distance traveled.

An emission factor (EF) relates pollutant emissions to an activity level:

$E = EF \times A$

Where:

- EF = emission factor
- A = activity data

Example 2: Emission Calculation Using EF

A diesel generator consumes 12,000 kg of fuel per day. The PM emission factor is 0.003 kg PM/kg fuel. Calculate E.

Solution:
$E = 12{,}000 \times 0.003 = 36$ kg PM/day

Example 3: Annual Emissions

Calculate E_{annual}.

$E_{annual} = 36 \times 365 = 13{,}140$ kg PM/year

5. Emission Inventory Basics

An emission inventory provides a comprehensive picture of pollutant releases within a defined geographic area. It serves as a cornerstone for air quality modeling, regulatory compliance, and policy development.

An emission inventory is a quantitative listing of emissions from all sources in a given area.

Components:

- Source identification.
- Emission factors.
- Activity levels.
- Temporal variation.
- Spatial distribution.

Inventories are used for:

- Air quality modeling.
- Regulatory compliance.
- Policy analysis.

Figure 10 presents three time-based emission profiles to illustrate how pollutant releases vary across different time scales. The hourly variation panel shows typical daily traffic peaks in the morning and evening, with lower emissions during mid-day and late night. The daily variation panel depicts weekday industrial activity, rising at the start of the week, peaking midweek, and slightly decreasing toward the end of the week. The seasonal variation panel illustrates higher emissions during winter (e.g., heating demand) and lower emissions during summer and fall. Together, the panels emphasize that emissions are not constant and must be temporally resolved for accurate dispersion modeling.

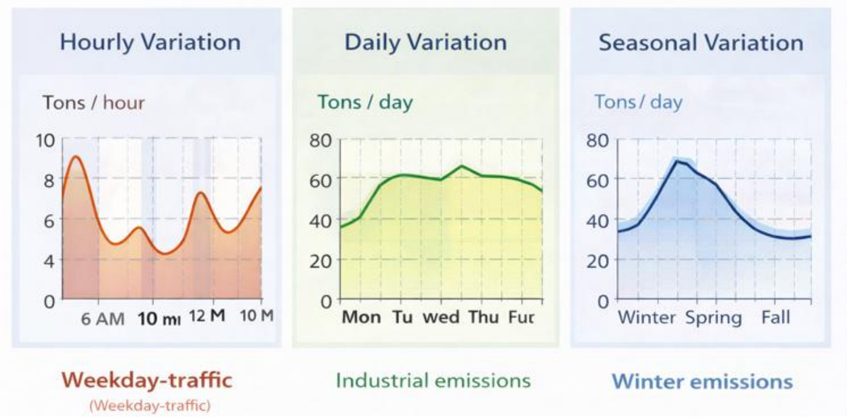


Figure 10: Temporal Emission Profile (Hourly / Daily / Seasonal)

Figure illustrates the spatial allocation of emissions within an urban region using a Geographic Information System (GIS). Emissions from different source categories are assigned to their geographic locations based on source characteristics and activity data. Point sources (e.g., industrial facilities and power plants) are represented at fixed locations, line sources (e.g., major roadways) follow transportation corridors, and area sources (e.g., residential and commercial zones) are distributed across land-use regions. Color shading represents emission intensity, with warmer colors indicating higher emission densities. Spatial allocation is a critical step in emission inventory development, as it enables realistic dispersion modeling and accurate estimation of population exposure.

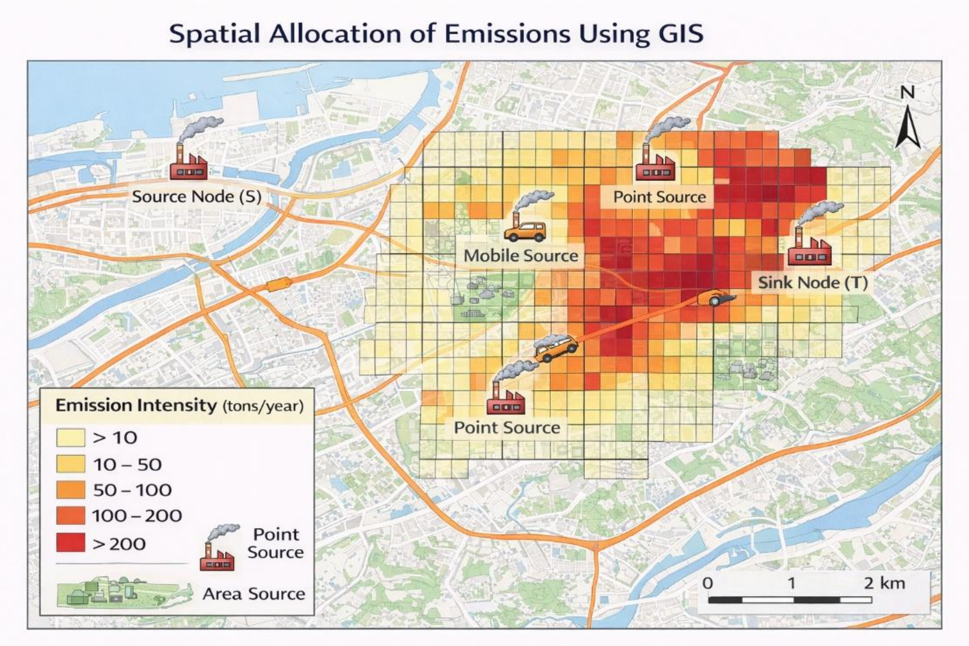


Figure 11: Spatial Allocation of Emissions Using GIS

Example 4: Inventory Summation

Calculate E_{total} for: (Source, Emissions (t/year)): (Boiler, 18), (Generator, 7), (Vehicles, 25).

E_{total} is calculated by applying a simple emission inventory summation, which is standard practice in air pollution engineering. Etotal = 18 + 7 + 25 = 50 t/year.

6. Mobile Sources and Vehicle Emissions

Mobile sources, particularly vehicles, are among the dominant contributors to urban air pollution. Their emissions vary widely depending on technology, fuel, and operating conditions, making them a key focus of modern air quality engineering.

Vehicle emissions depend on:

- Fuel type.
- Engine technology.
- Operating conditions.
- Vehicle age.

Major pollutants:

- CO
- NO_x
- VOCs
- PM

Example 5: Vehicle Fleet Emissions

100,000 vehicles emit 2 g NO_x/km. Average travel = 20 km/day. Calculate E.

E = 100,000 × 2 × 20 = 4,000,000 g/day
E = 4 t/day

7. Natural vs Anthropogenic Sources

Air pollutants originate from both natural processes and human activities. While natural sources can be significant, engineering efforts focus primarily on emissions that can be controlled through design, regulation, and technology.

Natural sources:

- Volcanoes.
- Wildfires.
- Dust storms.
- Biogenic VOCs.

Anthropogenic sources:

- Industry.
- Transportation.
- Power generation.

Engineering focus is primarily on anthropogenic emissions, which are controllable.

Example 6: A factory emits 5 g/s of SO_2 for 8 hours/day. Calculate E.

E = 5 × 3600 × 8 = 144,000 g/day = 144 kg/day

Example 7: Classify each source:

- Refinery stack → Point source
- Urban traffic → Line source
- Residential heating → Area source

8. Engineering Implications

Accurate identification and quantification of emission sources directly influence the reliability of air quality analyses. Errors at this stage propagate through models, control designs, and regulatory decisions.

Accurate source characterization:

- Determines model accuracy.
- Affects control design.
- Influences regulatory decisions.

Poor emission estimates lead to poor air quality predictions.

CHAPTER 4: EMISSION INVENTORY DEVELOPMENT AND DATA MANAGEMENT

1. Role of Emission Inventories in Air Pollution Engineering.

Emission inventories provide the quantitative foundation upon which air pollution analysis and control strategies are built. Without a reliable accounting of pollutant releases, engineers cannot accurately model air quality, assess health impacts, or evaluate the effectiveness of regulatory actions. As such, emission inventories represent one of the most critical tools in air pollution engineering practice.

An emission inventory is a systematic, quantitative accounting of pollutants released into the atmosphere from all sources within a defined geographic area and time period. Emission inventories form the foundation of nearly all air pollution engineering activities, including:

- Dispersion modeling.
- Health risk assessment.
- Regulatory permitting.
- Air quality management planning.
- Evaluation of control strategies.

From an engineering perspective, an emission inventory is not simply a list of numbers , it is a data-driven model that must be internally consistent, reproducible, and scientifically defensible.

2. Types of Emission Inventories.

Emission inventories are developed for different purposes and organized in different ways depending on regulatory, analytical, and planning needs. Classifying inventories helps engineers select appropriate data sources, methods, and levels of detail for a given application.

2.1 By Purpose

Inventories may be developed to describe existing conditions, evaluate future scenarios, or satisfy regulatory requirements. Each purpose dictates the level of accuracy, documentation, and conservatism required.

- Baseline inventories: represent existing conditions.
- Control strategy inventories: simulate future scenarios.
- Regulatory inventories: used for compliance and reporting.

2.2 By Source Category

Emission inventories are also classified according to the types of sources included. Each source category has distinct emission characteristics and requires specialized estimation techniques.

- Point source inventories.
- Mobile source inventories.
- Area source inventories.
- Biogenic inventories (often modeled separately).

Each category requires different data collection and estimation techniques. Note that inventories often overlap purposes (e.g., baseline inventories used for regulatory modeling).

3. Core Components of an Emission Inventory.

A well-developed emission inventory is built from several essential components that collectively describe where emissions originate, how frequently activities occur, and how pollutants are generated. Missing or inaccurate components can significantly compromise inventory quality. Figure 12 illustrates the emission inventory flowchart components.

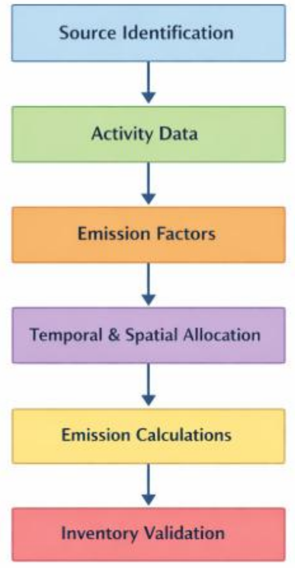


Figure 12: Emission Inventory Flowchart Components

3.1 Source Identification

The first step in inventory development is the identification of all relevant emission sources. Clear and consistent source identification ensures that emissions are not double-counted or omitted. Each emission source must be uniquely identified by:

- Location.
- Source type.
- Operating characteristics.

Table 4 represents an example of source identification.

Table 4: Example Source Identification

Source Type	Location/ID	Operating Characteristics	Notes
Boiler	Plant A Stack 1	24 h/day, 350 MW	Fossil fuel-fired
Generator	Plant B Gen 2	12 h/day, 10 MW	Backup diesel unit
Vehicles	City Fleet	08:00–18:00 daily	100,000 vehicles

3.2 Activity Data

Activity data describe the extent to which a source operates and serve as the quantitative link between real-world behavior and emissions. Accurate activity data are often the most challenging inventory inputs to obtain.

Examples:

- Fuel consumed (kg/year).
- Distance traveled (km/year).
- Operating hours (h/year).
- Production rate (tons/year).

3.3 Emission Factors

Emission factors translate activity levels into pollutant emissions. They provide a practical estimation method when direct measurement is not feasible.

Emission factors relate emissions to activity:

$E = EF \times A$

Emission factors are derived from:

- Stack testing.
- Laboratory experiments.
- Regulatory databases.

Table 5 represents the emission factors for key pollutants.

Table 5: Emission Factors (EF) for Key Pollutants

Source	Pollutant	Emission Factor (EF)	Unit	Notes
Boiler	SO_2	0.50	kg/MWh	Fuel-based EF
Boiler	PM	0.10	kg/MWh	Stack measurement derived
Generator	NO_x	1.8	g/km	Diesel engine
Vehicles	CO	2.0	g/km	Fleet average
Vehicles	$PM_{2.5}$	0.05	g/km	Average emission for light-duty vehicles

Note: The NO_x emission factor for the diesel generator is expressed in g/km based on equivalent engine-based emission data commonly used for compression-ignition engines. For stationary operation, this factor may alternatively be converted to g/kWh using fuel consumption and load characteristics.

4. Time and Spatial Allocation of Emissions

Total annual emissions alone are insufficient for most air quality analyses. Engineers must allocate emissions across time and space to accurately represent real-world conditions and support dispersion modeling.

4.1 Temporal Allocation

Emissions vary over time due to changes in operating schedules, human activity, and seasonal conditions. Temporal allocation distributes emissions into appropriate time intervals.

Emissions vary by:

- Hour of day.
- Day of week.
- Season.

Temporal profiles are required for:

- Short-term modeling.
- Episode analysis.

Table 6 illustrates the temporal allocation of emissions and Table 7 represents the fraction of annual emissions with time period.

Table 6: Temporal Allocation of Emissions

Source	Annual Emissions (t/year)	Daytime %	Nighttime %	Weekday %	Weekend %	Notes
Industrial Boiler	120	60	40	70	30	Day/night operational profile
Generator	36	50	50	80	20	Backup generator usage
Vehicles	25	70	30	75	25	Traffic pattern based

Example 1: Temporal Allocation

An industrial source emits 120 t/year of SO_2. If 60% occurs during daytime hours, calculate daytime emissions.

$E_{day} = 0.60 \times 120 = 72$ t/year

Table 7: Fraction of Annual Emissions with Time Period

Time Period	Fraction of Annual Emissions
Daytime (6-18h)	0.60
Nighttime (18-6h)	0.40

4.2 Spatial Allocation

Spatial allocation assigns emissions to specific geographic locations. This step is essential for capturing spatial gradients in pollutant concentrations, especially in urban environments.

Emissions must be distributed spatially using:

- Grid cells.
- Land-use data.
- Traffic density.

This is essential for urban-scale modeling.

5. Emission Calculations for Point Sources.

Point sources often provide the most detailed emissions data and are a primary focus of regulatory control. Engineers use stack measurements to calculate emission rates directly from measured concentrations and flow rates.

5.1 Stack-Based Emission Rate Calculation

For continuous emission sources, pollutant release rates are calculated using measured stack parameters. This method provides relatively high accuracy compared to factor-based estimates.

For continuous sources:

$E = C \times Q$

Where:

- C = pollutant concentration (g/m^3)
- Q = exhaust flow rate (m^3/s)

Figure 13 illustrates the stack-based emission rate calculation.

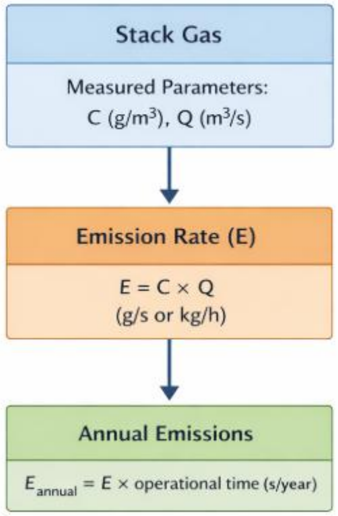


Figure 13: Stack-Based Emission Rate Calculation

Example 2: Stack Emission Rate

A stack emits gas at 15 m^3/s with SO_2 concentration of 0.20 g/m^3. Calculate E.

$E = 0.20 \times 15 = 3.0$ g/s

Example 3: Annual Emissions

Operating time = 3,000 h/year. Calculate E_{annual}.

$E_{annual} = 3.0 \times 3600 \times 3000 = 32.4$ t/year

6. Mobile Source Inventory Development

Mobile sources present unique challenges due to their movement, variability, and dependence on human behavior. Accurate mobile source inventories are essential for urban air quality management. Mobile sources require:

- Vehicle counts.
- Average travel distance.
- Emission factors by vehicle type.

Figure 14 illustrates the mobile source emission rate calculation.

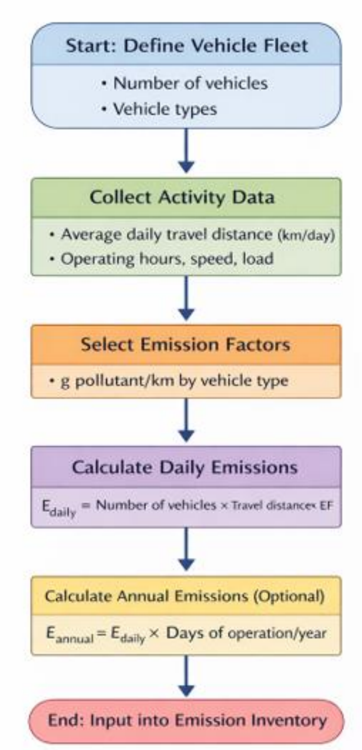


Figure 14: Mobile Source Emission Rate Calculation

Example 4: Fleet Emissions

50,000 vehicles emit 1.8 g NO_x/km and travel 25 km/day. Calculate E.

$E = 50{,}000 \times 1.8 \times 25 = 2{,}250{,}000$ g/day
E = 2.25 t/day

7. Area Source Inventory Example.

Area sources consist of many small, distributed emitters whose collective impact can be substantial. Estimating emissions from these sources typically relies on population-based or activity-based methods.

Example 5: Residential Heating

2,000 homes burn 1,200 kg fuel/year. EF = 0.004 kg PM/kg fuel. Calculate E.

$E = 2{,}000 \times 1{,}200 \times 0.004 = 9{,}600$ kg/year

8. Data Quality and Uncertainty.

All emission inventories contain some degree of uncertainty. Recognizing, quantifying, and managing this uncertainty is a critical responsibility of the engineer.

8.1 Sources of Uncertainty

Uncertainty arises from limitations in data quality, variability in operating conditions, and assumptions used in estimation methods.

- Inaccurate activity data.
- Outdated emission factors.
- Temporal variability.
- Measurement errors.

8.2 Engineering Judgment

Engineering judgment plays a key role in managing uncertainty. Transparent documentation and conservative assumptions help ensure that inventories remain defensible.

Engineers must:

- Document assumptions.
- Conduct sensitivity analysis.
- Use conservative estimates when required.

Example 6: Uncertainty Range

If EF uncertainty = ±20%:

$E = 100 \pm 20$ t/year

9. Emission Inventory Validation

Validation provides confidence that an emission inventory reasonably represents real-world conditions. Multiple validation approaches are often used to identify inconsistencies or errors.

Validation methods:

- Comparison with ambient measurements.
- Cross-checking fuel consumption data.
- Consistency checks across sectors.

10. Engineering and Regulatory Importance

High-quality emission inventories are essential for effective air quality management. They support regulatory decisions, improve model predictions, and guide the selection of cost-effective control measures.

Accurate inventories:

- Support defensible regulatory decisions.
- Improve model accuracy.
- Guide cost-effective controls.

Poor inventories lead to ineffective air quality management.

CHAPTER 5: ATMOSPHERIC DISPERSION FUNDAMENTALS

1. Introduction: Why Dispersion Matters.

Once emissions are quantified, the next critical task in air pollution engineering is to determine how those emissions behave after release into the atmosphere. Atmospheric dispersion governs the transport, spreading, and dilution of pollutants and ultimately determines ground-level concentrations experienced by human and environmental receptors. Dispersion analysis is therefore essential for linking emission rates to exposure, risk, and regulatory compliance, and it underpins engineering decisions related to source design and air quality management.

Once emissions are quantified (Chapter 4), engineers must predict how pollutants move, spread, and dilute in the atmosphere. Dispersion analysis is critical for:

- Estimating ground-level concentrations.
- Determining receptor exposure.
- Designing stack heights and control strategies.
- Ensuring compliance with air quality standards.

From an engineering perspective, dispersion is governed by advection, turbulent diffusion, and atmospheric stability.

2. Fundamental Processes in Atmospheric Dispersion.

Atmospheric dispersion results from the combined action of several physical processes that operate simultaneously in the lower atmosphere. These processes control how pollutants are transported away from their source and how rapidly they are diluted. Understanding each mechanism individually allows engineers to interpret dispersion behavior under different meteorological conditions and to apply appropriate modeling approaches. The key processes of atmospheric dispersion processes such as advection, turbulent diffusion, and vertical mixing are illustrated in Figure 15.

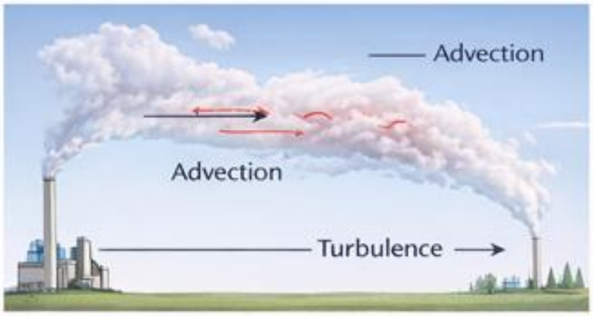


Figure 15: Atmospheric Dispersion Processes

2.1 Advection

Advection describes the horizontal transport of pollutants by the mean wind. It determines the direction, travel distance, and arrival time of a pollutant plume at downwind receptors. In engineering applications, advection establishes the basic movement of emissions and defines the time scale over which exposure may occur, particularly during short-term or accidental releases.

- Horizontal transport by the mean wind
- Governs travel distance and time
- Strong winds → faster downwind transport and reduced local concentrations

$$x = u \cdot t$$

Where:

- x = downwind distance (m)
- u = wind speed (m/s)
- t = travel time (s)

Example 1: Downwind Travel Time

Wind = 5 m/s; receptor = 1.5 km downwind. Calculate the time to reach the receptor.

$$t = \frac{1500}{5} = 300 \text{ s} = 5 \text{ min}$$

Interpretation:
Rapid transport can influence acute exposure during peak emissions.

2.2 Turbulent Diffusion

While advection moves pollutants as a whole, turbulent diffusion controls how the plume spreads and dilutes within the atmosphere. Turbulence arises from wind shear, surface roughness, and thermal convection, producing random air motions that disperse pollutants laterally and vertically. The strength of turbulent diffusion is a key determinant of ground-level concentration.

- Random air motion caused by wind shear and convection.
- Governs plume spread in both horizontal (σ_{γ}) and vertical (σ_{z}) directions.
- Strong turbulence → better dilution → lower concentrations.

2.3 Vertical Mixing and Stability

Vertical mixing depends on atmospheric stability, which reflects the resistance of the atmosphere to vertical motion. Stability conditions strongly influence whether pollutants are dispersed upward or trapped near the ground. Identical emission rates can therefore lead to very different air quality outcomes depending on atmospheric stability.

Atmospheric stability strongly affects how pollutants disperse from a source:

- Unstable (Convective): Strong vertical mixing spreads the plume widely, causing low ground-level concentrations**.**
- Neutral: Moderate mixing produces moderate spread and ground-level concentrations**.**
- Stable (Inversion): Limited vertical and horizontal mixing traps pollutants, resulting in a narrow plume with high ground-level concentrations.

The more stable the atmosphere, the less the plume disperses, increasing the risk of local air pollution. This principle is essential for designing stacks, modeling dispersion, and assessing exposure risks.

The effect of atmospheric stability and vertical mixing on plume dispersion and ground level concentrations are represented in Figure 16.

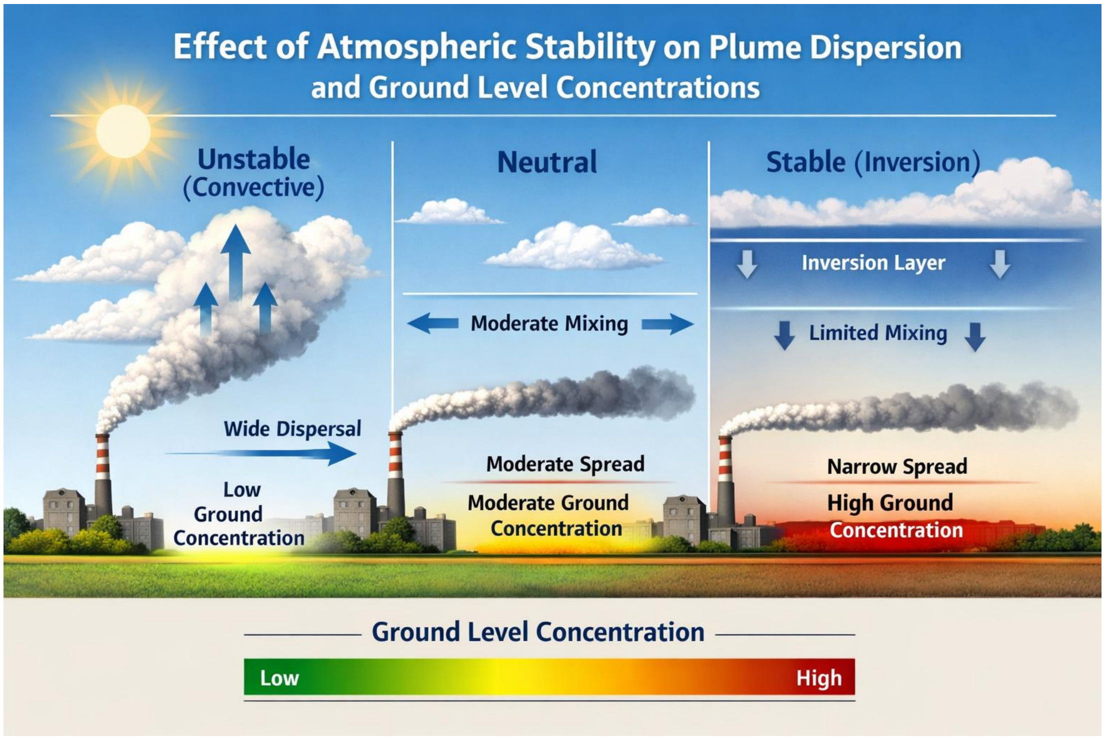


Figure 16: Effect of Atmospheric Stability on Plume Dispersion and Ground level Concentrations

Example 2: Stability Effect

Two identical stacks, same emissions:

- Case A: Unstable atmosphere → 100 $\mu g/m^3$
- Case B: Stable atmosphere → 300 $\mu g/m^3$

Conclusion:
Stability tripled pollutant concentration near the source.

3. Gaussian Plume Conceptualization.

To translate dispersion physics into engineering calculations, simplified conceptual models are used. The Gaussian plume model provides a practical framework for representing continuous emissions under steady-state conditions. Although detailed formulation is presented later, introducing the concept here helps establish how plume spreading and concentration decay are represented mathematically.

Although detailed formulation (Chapter 6) uses the Gaussian plume, fundamental dispersion principles are introduced here.

Key assumptions:

- Continuous emission from point source.
- Steady wind.
- Turbulent diffusion dominates.
- No chemical transformation.

Plume spreads in both horizontal and vertical directions, with concentration decreasing as distance from the source increases. An illustration of a Gaussian plume showing plume spread and concentrations is shown in Figure 17.

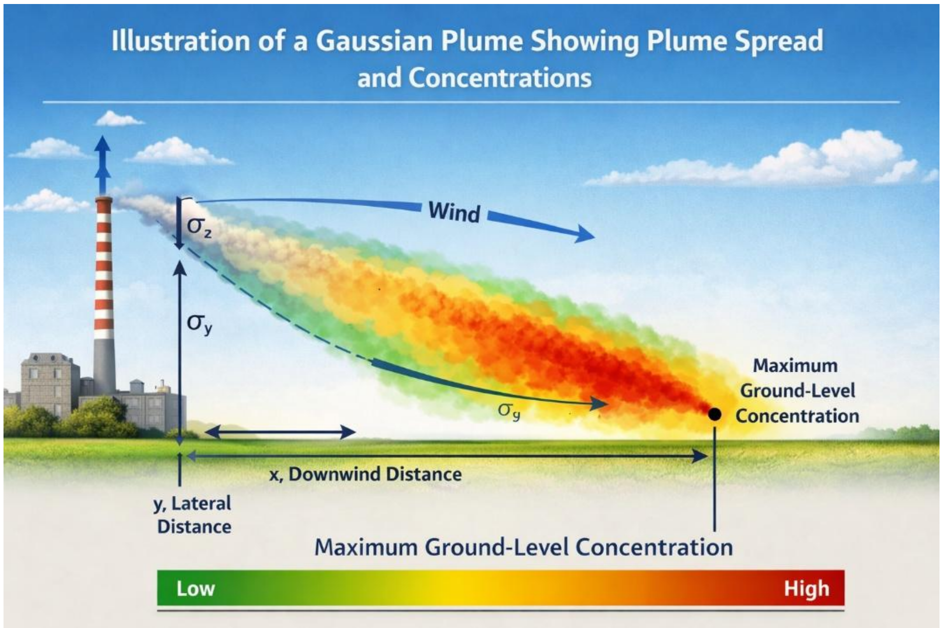


Figure 17: Illustration of a Gaussian Plume Showing Plume Spread and Concentrations

4. Turbulent Diffusion Coefficients

To quantify plume spreading, engineers use turbulent diffusion coefficients that represent the intensity of atmospheric turbulence. These coefficients vary with atmospheric stability and downwind distance and are typically obtained from empirical relationships developed through field observations.

Engineers quantify diffusion using turbulent diffusion coefficients:

- K_y→ horizontal
- K_z→ vertical

High turbulence → large K→ faster dilution

Empirical formulas often relate K to stability class and downwind distance.

An illustration of a plume spread with increasing downwind distance showing key parameters (horizontal and vertical spreads) is represented in Figure 18.

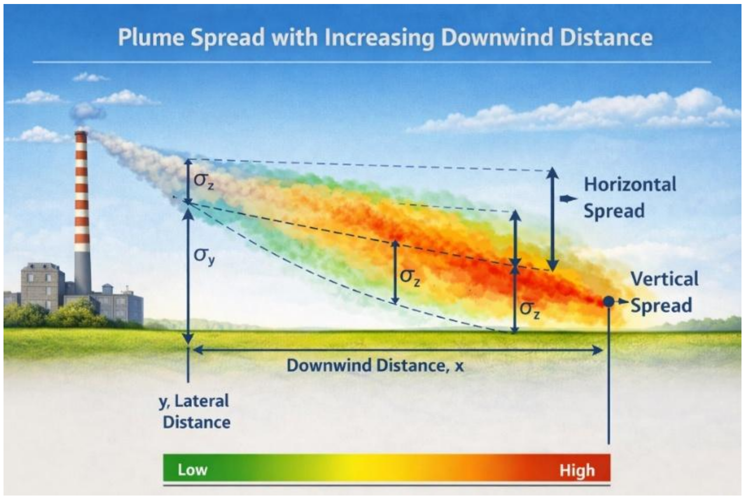


Figure 18: Plume Spread with Downwind Distance

Example 3: Vertical Diffusion Estimation

Downwind distance $x = 500$m, stability class D (neutral),

$$\sigma_z \approx 0.1x^{0.9}$$

Estimate σ_z:

$$\sigma_z = 0.1 \times 500^{0.9} \approx 0.1 \times 251 \approx 25 \text{ m}$$

5. Mixing Height and Dilution Volume

The mixing height defines the vertical depth of the atmosphere available for pollutant dispersion. It serves as an upper boundary for vertical mixing and plays a crucial role in determining average pollutant concentrations over an area. Mixing height is especially important in screening-level assessments and urban air quality studies.

Mixing height (H_m) defines the vertical extent of dispersion. This equation assumes uniform mixing within the defined control volume.

$$C_{avg} = \frac{E}{U \cdot H_m \cdot W}$$

Where each variable represents an air pollution engineering concept related to average pollutant concentration in a control volume. Specifically:

- C_{avg} = Average pollutant concentration (mass per unit volume, e.g., µg/m³ or g/m³).
- E = Emission rate (mass of pollutant emitted per unit time, e.g., g/s, kg/day).
- U = Wind speed (m/s), representing the horizontal transport velocity of the air.
- H_m = Mixing height (m), the vertical extent of the atmosphere in which pollutants can mix.
- W = Effective plume width or width of the area under consideration (m) perpendicular to the wind direction.

Mixing height concept showing the upper boundary of the atmospheric layer available for pollutant dispersion is illustrated in Figure 19.

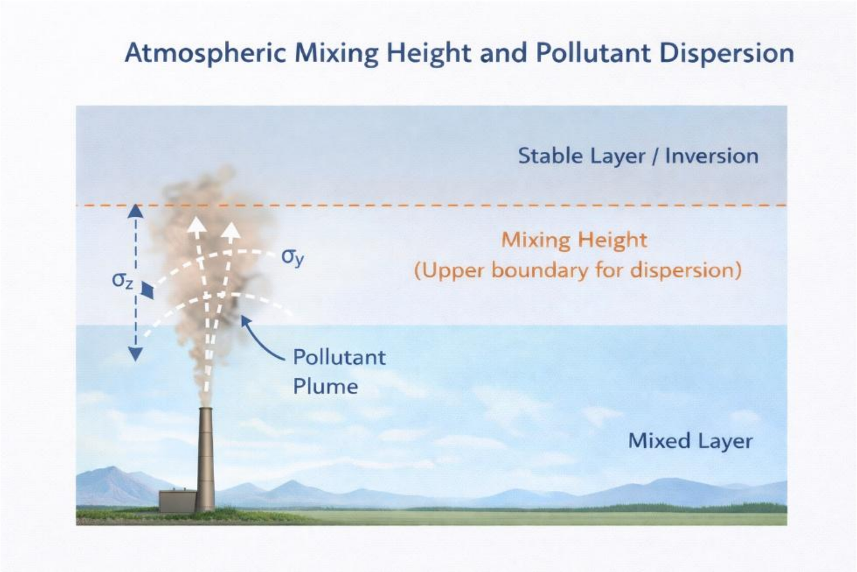


Figure 19: Mixing Height Concept

Example 4: Average Ground-Level Concentration

- $E = 100\text{g/s}$
- $U = 4\text{m/s}$
- Mixing height $H_m = 500\text{m}$
- Plume width $W = 200\text{m}$

$$C_{\text{avg}} = \frac{100}{4 \cdot 500 \cdot 200} = 0.00025\ \text{g/m}^3 = 250\ \mu\text{g/m}^3$$

Interpretation:
Engineers use this simplified calculation for preliminary assessment and screening.

6. Effects of Wind Speed on Dispersion.

Wind speed directly affects pollutant concentrations by controlling both transport and dilution. Higher wind speeds increase dispersion efficiency and reduce residence time near receptors. As a result, wind speed is one of the most influential variables in air quality modeling.

- Concentration is inversely proportional to wind speed:

$$C \propto \frac{1}{U}$$

- Doubling wind speed halves ground-level concentrations, all else equal.

A comparison of pollutant dispersion under low and high wind speed scenarios is illustrated in Figure 20.

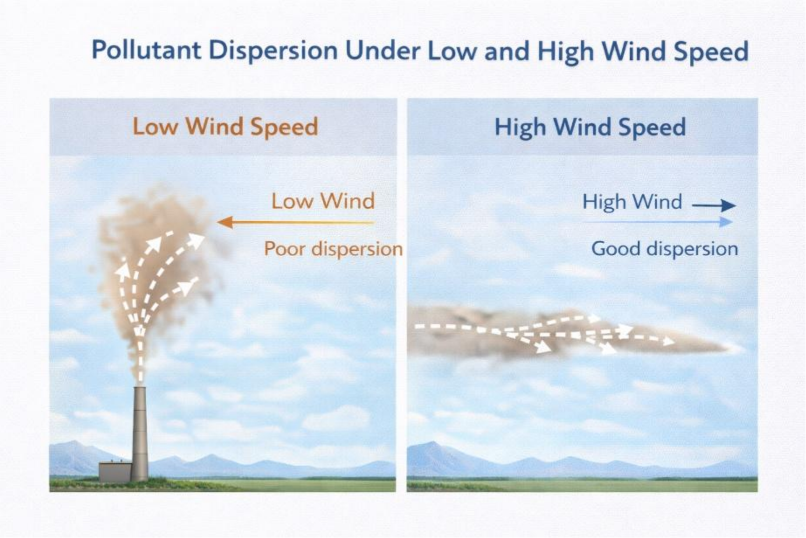


Figure 20: Effect of Wind Speed on Concentration

Example 5: Wind Speed Change

$C = 300\ \mu\text{g/m}^3$ at $U = 4\text{m/s}$. Wind doubles to 8 m/s. Calculate C_{new} assuming all other dispersion parameters remain constant.

$$C_{new} = 300 \times \frac{4}{8} = 150\ \mu\text{g/m}^3$$

7. Plume Behavior and Environmental Factors.

Beyond meteorology, plume behavior is influenced by source characteristics and surrounding environmental features. Stack temperature, exhaust velocity, terrain, and urban form can significantly alter dispersion patterns and exposure levels.

7.1 Buoyancy and Momentum

Thermal buoyancy and exit velocity determine plume rise above the source. Increased plume rise generally reduces ground-level concentrations by enhancing dilution before pollutants reach receptors.

- Hot stacks → plume rises → lower ground-level concentration.
- Cold stacks → low rise → higher concentration near source.

A comparison of plume rise due to buoyancy and momentum from hot and cold stacks is shown in Figure 21.

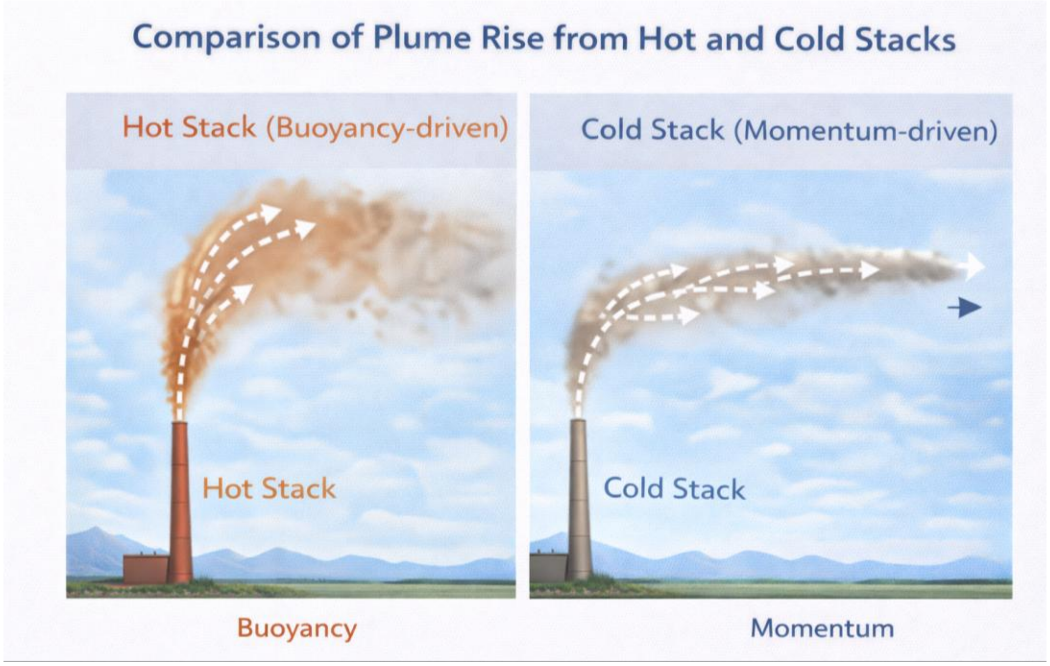


Figure 21: Plume Rise: Buoyancy and Momentum

7.2 Terrain Effects

Topography and urban structures can modify airflow and dispersion pathways. These effects are particularly important in complex terrain and densely built environments.

- Hills and valleys can channel or trap pollutants.
- Urban canyons increase pollutant retention.

Example 6: Preliminary Stack Height Assessment

Ground-level concentration target = 150 µg/m³
Emission = 100 g/s, wind = 4 m/s, $H_m = 500\text{m}$

Using simplified Gaussian assumptions:

$$C = \frac{E}{U \cdot H^* \cdot W} \Rightarrow H^* = \frac{E}{C \cdot U \cdot W}$$

$$H^* = \frac{100}{0.00015 \cdot 4 \cdot 200} \approx 833 \text{ m}$$

Interpretation:
Very tall stacks reduce ground-level exposure. Engineers may adjust plume rise or use dispersion controls.

7.3 Building Downwash Effects

Building downwash occurs when airflow interacting with nearby structures disrupts the plume emitted from a stack, causing enhanced turbulence and recirculation that can force pollutants downward toward the ground. When a stack is located near a building of comparable or greater height, the wind flow separates around the structure, creating a low-pressure wake region and a recirculation cavity on the downwind side. Emissions released into this region may be entrained into the cavity rather than dispersing freely, resulting in significantly elevated ground-level concentrations close to the source. Building downwash is particularly important for short stacks, rooftop vents, and industrial facilities in built-up environments. Because downwash can negate the benefits of plume rise and increased stack height, modern dispersion models such as AERMOD explicitly account for building effects using parameters based on building height, width, and orientation. Proper stack placement and sufficient stack height are therefore essential engineering controls to minimize downwash-induced impacts and ensure regulatory compliance.

An illustration of building downwash showing the enhanced ground level concentration near an upwind structure is represented in Figure 22.

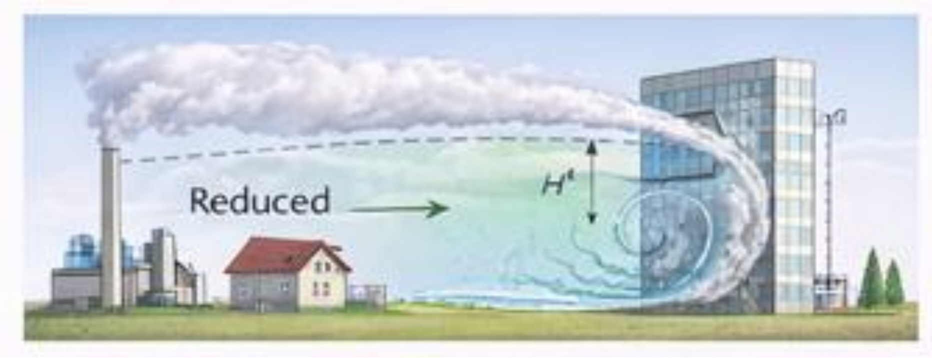


Figure 22: Building Downwash Effect

Example 7: Screening-Level Assessment of Building Downwash

Given:

- Stack height, $H_s = 30\text{m}$
- Nearby building height, $H_b = 25\text{m}$
- Emission rate, $E = 100\text{g/s}$
- Wind speed, $U = 4\text{m/s}$
- Effective plume width, $W = 200\text{m}$
- Mixing height, $H_m = 500\text{m}$

Step 1: Downwash Screening Criterion

A common screening rule is:

$$H_s < 2.5\,H_b \quad \Rightarrow \quad \text{Downwash likely}$$
$$2.5 \times 25 = 62.5\text{ m}$$

Since:

$$H_s = 30\text{ m} < 62.5\text{ m}$$

Downwash effects are likely and must be considered.

Step 2: Estimate Effective Stack Height Reduction

For screening purposes, assume the effective plume height is reduced to approximately the building height:

$$H_{\text{eff}} \approx H_b = 25\text{ m}$$

Step 3: Estimate Ground-Level Concentration Without Downwash

Using a simplified screening formula:

$$C = \frac{E}{U \cdot H_m \cdot W}$$

$$C = \frac{100}{4 \times 500 \times 200} = 0.00025 \text{ g/m}^3 = 250 \ \mu\text{g/m}^3$$

Step 4: Estimate Ground-Level Concentration With Downwash

Replace mixing height with the effective plume height to reflect limited vertical dispersion:

$$C_{\text{dw}} = \frac{E}{U \cdot H_{\text{eff}} \cdot W}$$

$$C_{\text{dw}} = \frac{100}{4 \times 25 \times 200} = 0.005 \text{ g/m}^3 = 5000 \ \mu\text{g/m}^3$$

Results Summary

Scenario	Effective Height (m)	Estimated Concentration (µg/m³)
No downwash	500	250
With downwash	25	5,000

Engineering Interpretation

Building downwash can increase near-source ground-level concentrations by an order of magnitude or more, particularly for short stacks near tall structures. This example demonstrates why downwash must be screened early in design and why regulatory dispersion models explicitly include building effects. In practice, engineers mitigate downwash by increasing stack height, relocating stacks away from buildings, or modifying exhaust velocity to enhance plume rise.

8. Summary of Dispersion Fundamentals.

Atmospheric dispersion is controlled by advection, turbulent diffusion, stability, and mixing height. These processes jointly determine pollutant transport, dilution, and exposure. Simplified calculations provide valuable screening insight before applying detailed dispersion models.

- Advection carries pollutants downwind.
- Turbulent diffusion spreads the plume.
- Stability and mixing height control dilution.
- Ground-level concentrations are highly sensitive to meteorology.
- Simplified calculations allow engineering screening before detailed modeling.

CHAPTER 6: GAUSSIAN PLUME MODEL

1. Introduction.

Once dispersion fundamentals are understood, engineers require a mathematical framework that can convert emission rates and meteorological conditions into predicted pollutant concentrations. The Gaussian plume model provides this framework and has become one of the most widely used tools in air pollution engineering. Its simplicity, analytical nature, and reasonable accuracy under steady conditions make it particularly valuable for screening analyses, regulatory permitting, and preliminary design studies involving continuous point sources.

The Gaussian plume model is a cornerstone of air pollution engineering for predicting ground-level concentrations downwind of a continuous point source (e.g., a smokestack).

Its advantages:

- Simple analytical form.
- Requires only emission rate, wind speed, and dispersion parameters.
- Useful for screening, permitting, and preliminary design.

Assumptions:

- Continuous point-source emission.
- Steady-state meteorology (constant wind and turbulence).
- Gaussian distribution in horizontal (y) and vertical (z) directions.
- No chemical reactions (for inert pollutants).
- Flat terrain.

Applicability Conditions

- Wind speed > 1 m/s.
- Continuous emissions.
- Receptor distance > 10 stack diameters.

2. Gaussian Plume Equation.

The Gaussian plume equation mathematically describes how pollutant concentration varies in space as a function of emission strength, wind speed, atmospheric turbulence, and source height. It assumes that the pollutant cloud spreads in a statistically normal (Gaussian) manner in both the horizontal and vertical directions while being transported downwind by the mean wind. The second exponential term represents an image source used to satisfy the zero-flux boundary condition at the ground surface. This section presents the governing equation used in most engineering applications.

For a ground-level receptor (z = 0):

$$C(x,y,0) = \frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left[-\frac{y^2}{2\sigma_y^2}\right]\left[\exp\left(-\frac{H^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(H+0)^2}{2\sigma_z^2}\right)\right]$$

Where:

- C = concentration (g/m³)
- Q = emission rate (g/s)
- u = wind speed (m/s)
- H = effective stack height (physical height + plume rise) (m)
- σ_y, σ_z = horizontal and vertical dispersion coefficients (m)
- x = downwind distance (m)
- y = crosswind distance (m)
- z = vertical distance from ground (m)

For the centerline (y = 0):

$$C(x,0,0) = \frac{Q}{2\pi u\sigma_y\sigma_z}\left[\exp\left(-\frac{H^2}{2\sigma_z^2}\right) + \exp\left(-\frac{H^2}{2\sigma_z^2}\right)\right] = \frac{Q}{\pi u\sigma_y\sigma_z}\exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

This is the most commonly used form for engineering calculations. The Gaussian plume from a point source is illustrated in Figure 23.

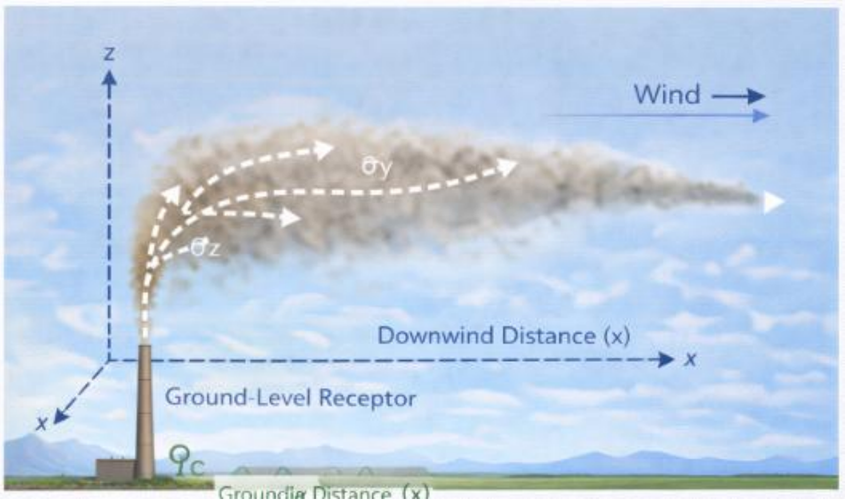


Figure 23: Gaussian Plume from a Point Source

3. Dispersion Coefficients (σ_γ, σ_z).

Dispersion coefficients quantify how rapidly a pollutant plume spreads as it moves downwind. These parameters incorporate the effects of atmospheric turbulence and stability and are essential inputs to the Gaussian plume equation. Because turbulence cannot be measured directly at all locations, empirical relationships are used to estimate dispersion coefficients as functions of distance and stability class. Dispersion coefficients increase monotonically with downwind distance and are strongly dependent on atmospheric stability.

- σ_y: horizontal spread, depends on downwind distance and stability class.
- σ_z: vertical spread, depends on downwind distance and stability class.

Pasquill–Gifford curves provide empirical relationships for $\sigma_y(x)$and $\sigma_z(x)$based on stability class (A–F).

Engineering tip:

- Unstable (A–B) → rapid spread → large σ
- Stable (E–F) → slow spread → small σ

3.1 Mixing Height

- If σ_z approaches mixing height, vertical reflection must be considered.
- Gaussian model may overpredict dilution if mixing height is ignored.

3.2 Temporal & Spatial Allocation

Temporal allocation

- Hourly (diurnal).
- Daily (weekday/weekend).
- Seasonal.

Spatial allocation

- GIS-based emission mapping.
- Required for area and line sources.
- Critical for regulatory inventories and dispersion inputs.

4. Effective Stack Height.

The effective stack height represents the actual height at which pollutants are released into the atmosphere after accounting for plume rise. Plume rise occurs because hot or fast-moving exhaust gases continue to ascend after leaving the stack. Plume rise results from both buoyancy (temperature difference) and momentum (exit velocity), with buoyancy dominating for hot exhausts and momentum dominating for high exit velocities. Accurately estimating effective stack height is critical, as it strongly influences predicted ground-level concentrations.

$$H_e = H_s + \Delta H$$

Where:

- H_s = physical stack height
- ΔH = plume rise due to buoyancy and momentum (m)

Plume rise formulas:

- Briggs formula for buoyant plumes.
- $\Delta H \propto F^{1/3}/u($ F = buoyancy flux).

Example 1: Centerline Ground-Level Concentration

Applying the Gaussian plume equation to a real-world scenario demonstrates how each parameter influences concentration. This example illustrates a typical engineering calculation for a receptor located directly downwind of an industrial stack.

Given:

- $Q = 120$g/s (SO₂)
- $u = 4$m/s
- $\sigma_y = 40$m
- $\sigma_z = 20$m
- $H_e = 60$m
- Receptor: downwind, $y = 0$

Calculate C.

Solution:

$$C = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

Step 1: Exponential term

$$\frac{H^2}{2\sigma_z^2} = \frac{60^2}{2 \cdot 20^2} = \frac{3600}{800} = 4.5$$

$$\exp(-4.5) \approx 0.0111$$

Step 2: Denominator

$$\pi \cdot u \cdot \sigma_y \cdot \sigma_z = 3.1416 \cdot 4 \cdot 40 \cdot 20 \approx 10{,}053$$

Step 3: Multiply by Q and exponential

$$C = \frac{120}{10{,}053} \cdot 0.0111 \approx 0.000132 \text{ g/m}^3 = 132\, \mu\text{g/m}^3$$

Interpretation:
This is a reasonable mid-range concentration for an industrial stack.

5. Sensitivity to Wind Speed.

Wind speed plays a dominant role in dispersion modeling because it directly affects dilution. Even small changes in wind speed can significantly alter predicted concentrations, making sensitivity analysis an essential part of engineering judgment.

Rule:

$$C \propto \frac{1}{u}$$

Example 2: Wind doubles to $u = 8$m/s:

$$C_{new} = 132 \times \frac{4}{8} = 66\, \mu\text{g/m}^3$$

Conclusion:
Doubling wind speed halves ground-level concentration, all else equal.

6. Sensitivity to Stack Height.

Stack height affects concentrations exponentially through the vertical dispersion term. Increasing effective stack height enhances dilution by allowing greater plume spread before pollutants reach the ground.

Rule:

$$C \propto \exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

Example 3: H_e increases from 60 m → 80 m, calculate C:

$$\frac{H^2}{2\sigma_z^2} = \frac{80^2}{2 \cdot 20^2} = \frac{6400}{800} = 8$$

$$\exp(-8) \approx 0.000335$$

$$C = \frac{120}{10{,}053} \cdot 0.000335 \approx 0.004\,\mu\text{g/m}^3$$

Conclusion:
Raising stack height dramatically reduces ground-level concentrations.

7. Crosswind Dispersion.

Pollutant concentrations decrease rapidly as distance from the plume centerline increases. This behavior is important for land-use planning, zoning decisions, and evaluating impacts on nearby communities.

$$C(x, y, 0) \propto \exp\left(-\frac{y^2}{2\sigma_y^2}\right)$$

Engineering interpretation:

Receptors located off-center receive significantly lower concentrations. Spatial planning and zoning are therefore important.

Example 4: Crosswind Concentration

$y = 20$m, $\sigma_y = 40$m. Calculate C.

$$\exp\left(-\frac{y^2}{2\sigma_y^2}\right) = \exp\left(-\frac{400}{2 \cdot 1600}\right) = \exp(-0.125) \approx 0.882$$

$$C \approx 132 \times 0.882 \approx 116\ \mu\text{g/m}^3$$

Interpretation:
12% lower than centerline concentration at 20 m crosswind.

8. Limitations of the Gaussian Model.

While widely used, the Gaussian plume model has well-defined limitations that engineers must recognize. Understanding these constraints ensures that the model is applied appropriately and that more advanced tools are used when necessary.

- Steady-state assumption → poor for short-term fluctuating winds.
- Flat terrain assumption → inaccurate in mountains or valleys.
- No chemical reactions → inaccurate for reactive pollutants.
- Poor for very close or very far receptors relative to stack.

Engineering approach:

Use for screening, permitting, or preliminary design, then refine with computational fluid dynamics (CFD) or advanced dispersion models as needed.

9. Engineering Summary

Ground-level concentration increases with emission rate and decreases with wind speed, dispersion, and effective stack height. Atmospheric stability controls σ_γ and σz and therefore dominates dispersion behavior.

Chapter 7: Plume Rise and Stack Design

1. Introduction.

The design of smokestacks and understanding plume rise are fundamental to controlling ground-level concentrations of pollutants. Even with accurate emission quantification and dispersion modeling, poor stack design can result in excessive pollutant exposure near the source. Engineers must evaluate buoyancy, momentum, atmospheric stability, and surrounding terrain to determine effective stack height. Proper design reduces concentrations at sensitive receptors, ensures regulatory compliance, and informs environmental impact assessments.

2. Factors Affecting Plume Rise.

Plume rise occurs due to buoyancy (temperature difference between stack gas and ambient air) and momentum (exit velocity). Key factors include:

- Stack gas temperature and density.
- Exit velocity.
- Ambient wind speed.
- Atmospheric stability.
- Stack diameter and orientation.

Understanding these parameters allows engineers to predict how high a plume will rise and how far it will travel before reaching ground level.

3. Effective Stack Height.

The effective stack height (H_e) accounts for the physical stack height (H_s) plus the additional height gained by plume rise (ΔH):

$$H_e = H_s + \Delta H$$

- H_s: physical height of the stack (m)
- ΔH: plume rise due to buoyancy and momentum (m)

Plume rise formulas are based on Briggs equations:

- For buoyant plumes:

$$\Delta H \propto F^{1/3}/u$$

where F = buoyancy flux, u = wind speed

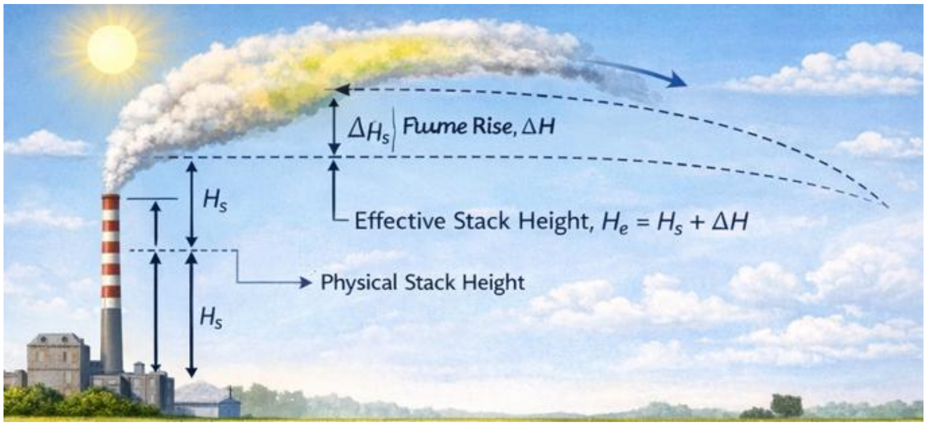
- For momentum-dominated plumes:

$$\Delta H \propto \frac{v_s d_s}{u}$$

where v_s = exit velocity, d_s = stack diameter, u = wind speed

Engineers must select the appropriate formula based on stack conditions.

Figure 24 illustrates the Plume Rise and Effective Stack Height.



4. Buoyant and Momentum Plume Equations.

Plume rise differs based on whether buoyancy or momentum dominates.

Figure 25 illustrates the Buoyant vs Momentum-Dominated Plumes.

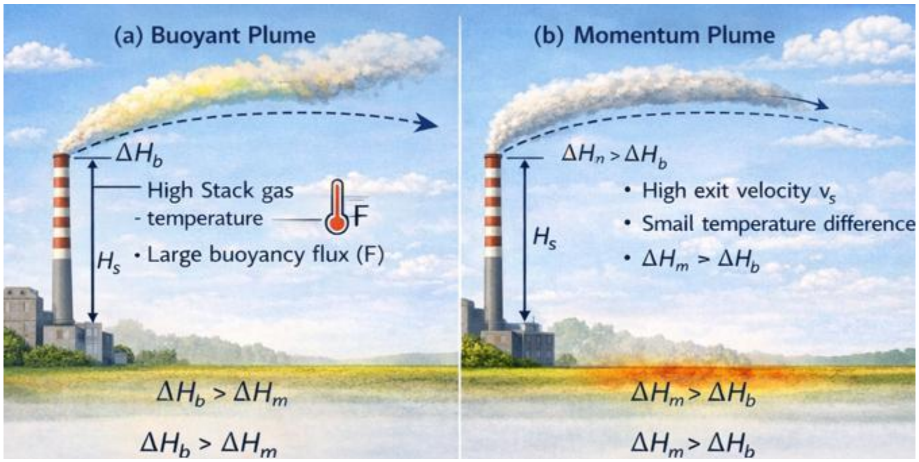


Figure 24: Buoyant vs Momentum-Dominated Plumes

Buoyant plume (strong temperature difference):

$$\Delta H_b = 1.6\left(\frac{F}{u}\right)^{1/3}$$

Momentum plume (high exit velocity, small temperature difference):

$$\Delta H_m = 3.0\,\frac{v_s d_s}{u}$$

Engineering note: The larger of ΔH_b and ΔH_m is typically used for effective stack height calculation.

Example 1: Plume Rise Calculation

A smokestack emits gases at 120°C, ambient temperature = 25°C. Exit velocity = 15 m/s, stack diameter = 2 m, wind speed = 4 m/s. Determine the plume rise.

Solution:

1. Buoyant rise:

$$\Delta H_b = 1.6\left(\frac{F}{u}\right)^{1/3} = 1.6\left(\frac{1.2\times 10^6}{4}\right)^{1/3} \approx 54\ \mathrm{m}$$

2. Momentum rise:

$$\Delta H_m = 3\,\frac{v_s d_s}{u} = 3\,\frac{15\cdot 2}{4} = 22.5\ \mathrm{m}$$

Conclusion:
Effective plume rise is governed by buoyancy, so ΔH ≈ 54 m.
If stack height $H_s = 60$ m → $H_e = 60 + 54 = 114$ m.

Example 2: Effective Stack Height Calculation

A factory emits hot exhaust gases through a stack with the following parameters:

- Physical stack height: $H_s = 50\text{ m}$
- Stack gas temperature: $T_s = 150^\circ\text{C}$
- Ambient air temperature: $T_a = 25^\circ\text{C}$
- Exit velocity of gas: $v_s = 20\text{ m/s}$
- Stack diameter: $d_s = 2.5\text{ m}$
- Wind speed: $u = 5\text{ m/s}$
- Buoyancy flux: $F = 2 \times 10^6\text{ m}^4/\text{s}^3$

Task:

1. Calculate the plume rise due to buoyancy (ΔH_b) and momentum (ΔH_m).
2. Determine the effective stack height H_e.

Solution

Step 1: Buoyant plume rise (Briggs formula)

$$\Delta H_b = 1.6\left(\frac{F}{u}\right)^{1/3}$$
$$\Delta H_b = 1.6\left(\frac{2 \times 10^6}{5}\right)^{1/3} = 1.6(4 \times 10^5)^{1/3}$$
$$\Delta H_b \approx 1.6 \cdot 74.0 \approx 118.4\text{ m}$$

Step 2: Momentum plume rise (Briggs formula)

$$\Delta H_m = 3.0\frac{v_s d_s}{u}$$
$$\Delta H_m = 3.0\frac{20 \cdot 2.5}{5} = 3.0\frac{50}{5} = 3.0 \cdot 10 = 30\text{ m}$$

Step 3: Determine effective stack height

$$H_e = H_s + \max\,(\Delta H_b, \Delta H_m)$$
$$H_e = 50 + \max\,(118.4,30) = 50 + 118.4 = 168.4\text{ m}$$

Answer:

- Buoyant rise: $\Delta H_b \approx 118\text{ m}$
- Momentum rise: $\Delta H_m = 30\text{ m}$
- Effective stack height: $H_e \approx 168\text{ m}$

Interpretation:
The plume is buoyancy-dominated, so the effective stack height is much higher than the physical stack. This higher plume reduces ground-level pollutant concentrations near the source.

Example 3: Impact on Ground-Level Concentration

Q = 120 g/s (SO_2), σ_y = 40 m, σ_z = 20 m, wind speed u = 4 m/s, effective stack height H_e = 114 m. Determine centerline ground-level concentration.

$$C(x,0,0) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{H_e^2}{2\sigma_z^2}\right)$$

1. Exponential term:

$$H_e^2/(2\sigma_z^2) = 114^2/(2 \cdot 20^2) = 12996/800 = 16.245$$

$$\exp(-16.245) \approx 8.8 \times 10^{-8}$$

2. Denominator:

$$\pi u \sigma_y \sigma_z = 3.1416 \cdot 4 \cdot 40 \cdot 20 \approx 10053$$

3. Multiply by Q and exponential:

$$C = \frac{120}{10053} \cdot 8.8 \times 10^{-8} \approx 1.05 \times 10^{-6} \text{ g/m}^3 = 0.00105\ \mu\text{g/m}^3$$

Interpretation:
Raising the stack height drastically reduces ground-level exposure.

Figure 26 illustrates the effect of effective stack height on ground-level concentration.

Figure 25: Effect of Effective Stack Height on Ground-Level Concentration

5. Stack Design Considerations.

Engineers must balance several factors:

- **Regulatory limits:** Maintain concentrations below standards.
- **Material and construction:** Taller stacks increase costs.
- **Local terrain and buildings:** Influence plume rise and dispersion.
- **Meteorology:** Stability, wind speed, and mixing height determine dilution efficiency.

Proper stack design minimizes local air quality impacts while remaining cost-effective.

6. Sensitivity Analysis.

6.1 Wind Speed

$C \propto 1/u$ → doubling wind speed halves ground-level concentration.

Example 3: If wind doubles from 4 → 8 m/s, $C_{new} = 0.00105 \times 0.5 \approx 0.000525$ µg/m³.

6.2 Stack Height

$C \propto \exp(-H_e^2 / 2\sigma\_z^2)$ → increasing stack height reduces concentrations exponentially.

Example 4: H_e increases from 114 → 130 m: exponential term decreases further, further lowering C.

7. Limitations of Plume Rise Models.

- Assumes steady-state meteorology → poor for fluctuating winds.
- Assumes flat terrain → inaccurate in complex topography.
- No chemical reactions → unsuitable for reactive pollutants.
- Very close (< 1–2 stack diameters) or far (> 10 km) receptors require advanced modeling.

Engineering approach: Use for screening, permitting, and preliminary design, then refine with CFD or advanced models if necessary.

CHAPTER 8: INDOOR AIR POLLUTION AND MASS BALANCE MODELING

Indoor air pollution (IAP) has become a major environmental and public health concern because people spend 80–90% of their time indoors. Unlike outdoor air pollution, indoor environments are enclosed systems, where pollutant concentrations are governed primarily by generation rates, ventilation, deposition, and removal mechanisms. From an engineering standpoint, indoor air quality (IAQ) problems are analyzed using control volume mass balance principles.

Indoor air pollution is particularly important in:

- Office buildings.
- Schools and universities.
- Hospitals.
- Residential buildings.
- Industrial workplaces.

Common indoor pollutants include carbon monoxide (CO), volatile organic compounds (VOCs), formaldehyde, radon, particulate matter ($PM_{2.5}$), and biological contaminants. Engineers design ventilation systems to maintain concentrations below health-based standards such as WHO, ASHRAE, and OSHA limits.

1. Sources of Indoor Air Pollution.

Indoor pollutant sources can be grouped into indoor sources, outdoor infiltration, and human activity. Indoor sources include combustion appliances, smoking, cleaning agents, and building materials. Outdoor infiltration brings in pollutants from traffic or industrial emissions. Human activities like cooking and cleaning add episodic emissions. Understanding source strength is essential for designing effective ventilation and filtration systems to maintain healthy indoor air.

2. Ventilation and Air Exchange

Ventilation is the primary engineering control for indoor air pollution. It dilutes and removes pollutants from indoor spaces. The air change rate is defined as:

$$ACH = \frac{Q}{V}$$

Where:

- Q = ventilation rate (m^3/h)
- V = room volume (m^3)

Higher air change rates reduce pollutant concentration but increase energy consumption. Engineers must balance air quality with energy efficiency when designing ventilation systems.

Example 1: Calculating Air Changes per Hour (ACH)

An office room has the following characteristics:

- Room volume: $V = 120$ m³
- Mechanical ventilation supplies air at a rate of $Q = 360$ m³/h

Task:

1. Calculate the air change rate (ACH).
2. Determine how long it would take to completely replace the room air once.

Solution

Step 1: Calculate ACH

$$\mathrm{ACH} = \frac{Q}{V}$$
$$\mathrm{ACH} = \frac{360}{120} = 3\ \mathrm{h}^{-1}$$

Interpretation:
The room air is replaced 3 times per hour, meaning every 20 minutes the volume of air equivalent to the room is exchanged.

Step 2: Time to completely replace the air once

$$t = \frac{60\ \mathrm{min}}{\mathrm{ACH}} = \frac{60}{3} = 20\ \mathrm{min}$$

Answer:

- Air change rate (ACH): 3 h^{-1}.
- Time for one full air replacement: 20 minutes.

Engineering note:

Increasing Q(ventilation rate) increases ACH and improves indoor air quality, but may also increase energy use for heating or cooling the supplied air. Engineers must optimize ACH based on occupancy, pollutant sources, and energy considerations.

3. Steady-State Mass Balance Model.

For a well-mixed indoor space at steady state, the indoor concentration is determined by:

$$C_{in} = C_{out} + \frac{G}{Q}$$

Where:

- C_{in}= indoor concentration (mg/m³)
- C_{out}= outdoor concentration (mg/m³)
- G = pollutant generation rate (mg/h)
- Q = ventilation rate (m³/h)

This equation is the foundation of indoor air quality engineering, allowing engineers to estimate concentrations based on source strength and ventilation. Figure 27 illustrates the indoor air pollution mass balance in a well-mixed room.

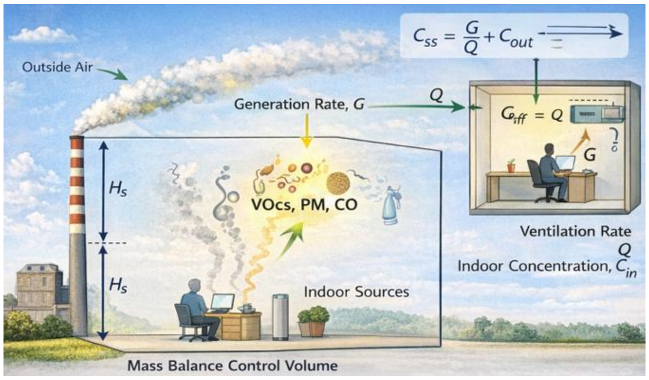


Figure 26: Indoor Air Pollution Mass Balance in a Well-Mixed Room

Example 2: CO generation = 30 mg/h, ventilation = 300 m³/h, outdoor CO = 1 mg/m³, find indoor concentration.

Solution:

$$C_{in} = 1 + \frac{30}{300} = 1.10 \text{ mg/m}^3$$

Example 3: Maximum VOC concentration = 0.05 mg/m³, generation = 40 mg/h, find Q.

Solution:

$$Q = \frac{40}{0.05} = 800 \text{ m}^3\text{/h}$$

4. Transient Mass Balance.

For time-varying conditions, indoor concentration changes with time according to:

$$V\frac{dC}{dt} = G - QC$$

Solution:

$$C(t) = \frac{G}{Q}\left(1 - e^{-Qt/V}\right)$$

This allows engineers to model how indoor pollutant concentrations evolve over time after a source starts or ventilation changes. Figure 28 illustrates the steady-state and transient indoor pollutant concentrations.

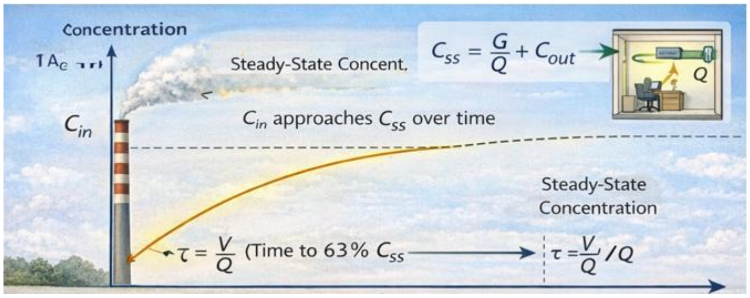


Figure 27: Steady-State and Transient Indoor Pollutant Concentrations

Example 4: Room volume = 200 m³, generation = 50 mg/h, ventilation = 250 m³/h, find concentration after 2 hours.

Solution:

$$C(2h) = \frac{50}{250}\left(1 - e^{-250 \cdot 2/200}\right) \approx 0.184 \text{ mg/m}^3$$

5. Filtration and Indoor PM Control.

Filtration enhances effective ventilation for particulate matter ($PM_{2.5}$). Effective ventilation is:

$$Q_{eff} = Q \times \text{filter efficiency}$$

Filtration removes suspended particles and is particularly important in sensitive environments like hospitals or schools. Figure 29 illustrates the effect of filtration on effective ventilation and $PM_{2.5}$ concentration.

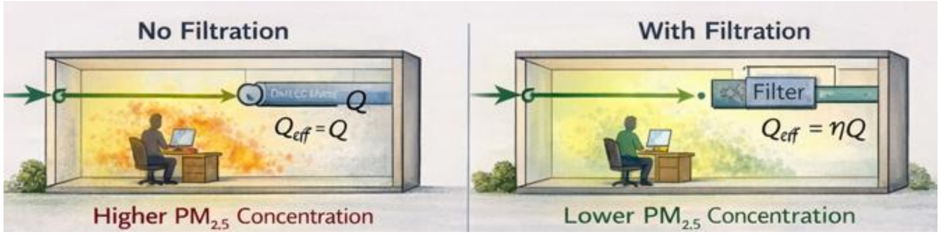


Figure 28: Effect of Filtration on Effective Ventilation and $PM_{2.5}$ Concentration

Example 5: Ventilation = 500 m³/h, filter efficiency = 70%, find effective ventilation.

Solution:

$$Q_{eff} = 500 \times 0.7 = 350 \text{ m}^3\text{/h}$$

6. Health-Based Standards.

Engineers design indoor air systems to maintain pollutants below recommended exposure limits as listed in Table 8.

Table 8: Recommended Exposure Limits

Pollutant	Limit
CO	9 ppm (8-hr)
$PM_{2.5}$	15 µg/m³ (annual)
Formaldehyde	0.1 mg/m³

Compliance ensures protection of occupants' health.

7. Summary

Indoor air pollution is governed primarily by mass balance principles. Ventilation and filtration are the primary control strategies, while source identification and proper building design complement these controls. Engineers must account for both steady-state and transient conditions to predict exposure accurately.

CHAPTER 9: HEALTH AND ENVIRONMENTAL IMPACTS OF AIR POLLUTION

1. Introduction.

Air pollution has direct consequences on human health, ecosystems, materials, and the climate. Understanding these impacts allows engineers to design effective control measures, evaluate regulatory compliance, and protect public health and the environment. This chapter connects emission and dispersion calculations to health outcomes and environmental consequences.

Air pollution impacts are typically evaluated through:

- Exposure assessment (concentration × time).
- Dose-response relationships.
- Risk characterization.
- Environmental damage metrics.

2. Human Health Impact Pathway.

Air pollutants follow a sequence from emission to measurable health effects. Engineers need to understand this pathway in order to evaluate how design and control strategies influence human health outcomes. By assessing each stage, it is possible to prioritize interventions and reduce overall risk.

Standard pathway:

Emission → Ambient Concentration → Exposure → Dose → Health Effect

Engineers influence the first two stages directly through design and control, while understanding the downstream consequences is essential for risk assessment. The standard exposure pathway for air pollutants and highlights where engineering interventions can reduce risk is illustrated in Figure 30.

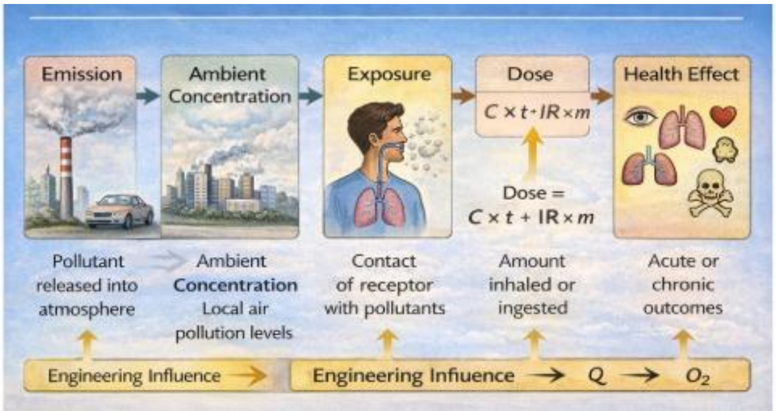


Figure 29: Human Health Impact Pathway

3. Exposure and Dose Concepts.

Quantifying exposure and dose is fundamental in linking pollutant concentrations to health risk. Exposure measures the contact of a receptor with pollutants over time, whereas dose reflects the actual amount of pollutant entering the body. These calculations provide the basis for regulatory limits and safety assessments.

3.1 Exposure

Exposure represents the contact between a pollutant and a receptor over a specific period:

Exposure = $C \times t$

Where:

- C = pollutant concentration (µg/m³)
- t = exposure time (h)

3.2 Dose

Dose accounts for the actual amount of pollutant inhaled by a person:

Dose = $C \times t \times IR \times m$

Where:

- IR = inhalation rate (m³/h)

The calculation of the exposure and dose for air pollution risk assessment is represented in Figure 31.

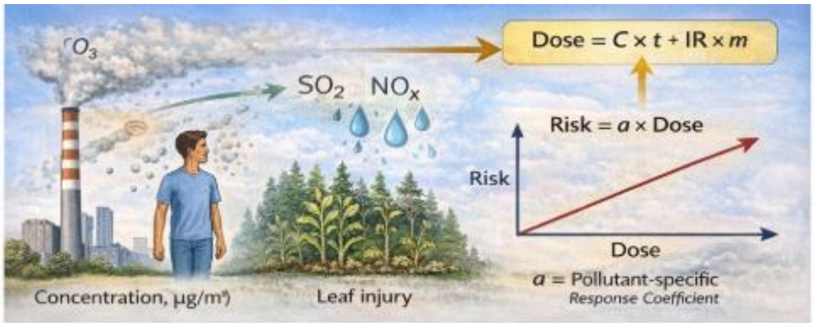


Figure 30: Calculating Exposure and Dose for Air Pollution Risk Assessment

Example 1: Daily Inhaled Dose

- $PM_{2.5}$ concentration = 35 µg/m³
- Exposure time = 16 h/day
- Adult inhalation rate = 0.75 m³/h

Calculate the dose.

Solution:
Dose = 35 × 0.75 × 16 = 420 µg/day

Interpretation: This dose can be compared with epidemiological thresholds to assess risk.

4. Acute vs Chronic Health Effects.

Air pollutants produce both short-term and long-term health effects. Acute effects arise from immediate exposure and may include irritation or respiratory symptoms, while chronic effects develop over years of exposure and can result in serious disease or premature death. Understanding these distinctions informs both engineering controls and public health guidelines.

Acute Effects (Short-term):

- Eye and throat irritation.
- Asthma attacks.
- Headaches.

Chronic Effects (Long-term):

- Cardiovascular disease.
- Lung cancer.
- Reduced lung function.
- Premature mortality.

Pollutants such as $PM_{2.5}$ and ozone are especially linked to chronic mortality risk. A comparison of acute vs chronic effects in a single infographic, with icons for eyes, lungs, heart, and mortality is illustrated in Figure 32.

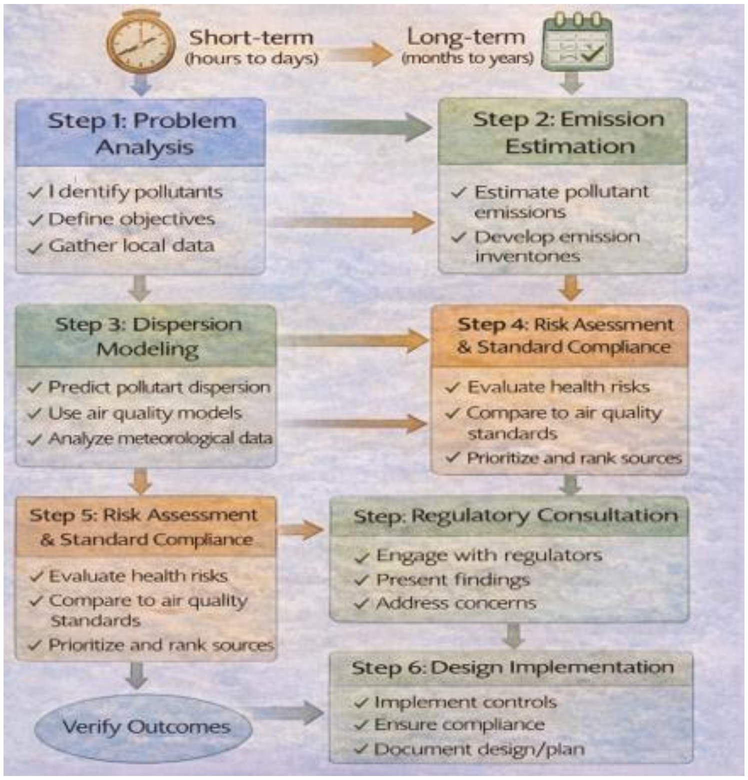


Figure 31: Comparison of Acute vs Chronic Effects

5. Dose–Response Relationships.

The dose–response relationship describes how health outcomes depend on the magnitude of exposure or dose. Engineers use these relationships to estimate population risk and guide design standards. Simplified linear models often suffice for preliminary assessments.

Simplified linear model:

$\text{Risk} = a \times \text{Dose}$

Where a is a pollutant-specific response coefficient derived from epidemiological studies.

Example 2: Risk Estimation

- Daily $PM_{2.5}$ dose = 420 µg/day
- Risk coefficient $a = 1.2 \times 10^{-6}$ per µg

Calculate the risk.

Solution:
Risk = $1.2 \times 10^{-6} \times 420 = 5.04 \times 10^{-4}$

Interpretation: Approximately 5 excess cases per 10,000 exposed individuals.

6. Vulnerable Populations.

Certain groups are more sensitive to air pollution due to age, health status, or physiological conditions. Engineers account for this variability by applying additional safety margins in exposure limits and control strategies, ensuring adequate protection for all populations.

Examples of vulnerable populations:

- Children.
- Elderly.
- Pregnant women.
- Individuals with asthma or heart disease.

7. Environmental Impacts of Air Pollution.

Air pollution affects ecosystems and materials in addition to human health. Engineers must evaluate these impacts to support sustainable design and mitigation strategies. Environmental assessments consider vegetation, soil, water quality, and building integrity.

7.1 Vegetation Damage

- Ozone reduces crop yields.
- SO_2 causes leaf injury.

7.2 Acid Deposition

- SO_2 and NO_x form sulfuric and nitric acid.
- Impacts forests, soils, and water bodies.

7.3 Material Damage

- Corrosion of metals.
- Degradation of limestone and concrete.

Figure 33 illustrates how the pollutants affect vegetation, acid deposition, and materials.

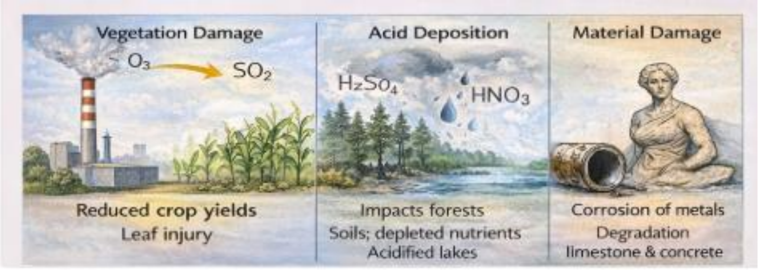


Figure 32: Environmental Impacts of Air Pollution on Ecosystems and Materials

Example 3: Acid Deposition Potential

- SO_2 emissions = 500 kg/day
- Conversion to sulfuric acid equivalent (H_2SO_4)
- Molecular weights: SO_2 = 64, H_2SO_4 = 98

Calculate the sulfuric acid equivalent.

Solution:
Sulfuric acid equivalent = 500 × 98 / 64 = 766 kg/day

8. Environmental Impact Metrics.

Engineers quantify environmental impacts using standard indicators, which allow comparisons across pollutants and regions. These metrics guide mitigation priorities and regulatory compliance.

Common metrics include:

- Excess mortality per 100,000 people.
- Crop yield loss (%).
- Visibility reduction (km).
- Ecosystem acid neutralizing capacity (ANC).

9. Air Pollution and Environmental Justice.

Communities with lower income or limited resources often experience higher pollutant exposure and greater health impacts. Engineering practice now incorporates equity considerations into air quality planning, aiming to reduce disparities in environmental health outcomes.

10. Summary of Engineering Implications.

- Health impacts justify strict air quality standards.
- Exposure and dose calculations link engineering to public health.
- Vulnerable populations require conservative design.
- Environmental damage extends beyond human health.

CHAPTER 10: AIR QUALITY STANDARDS, AQI, AND REGULATORY FRAMEWORKS

1. Introduction.

Air quality standards establish allowable concentrations of pollutants based on their health and environmental effects. These limits provide engineers with quantitative targets for emission control, monitoring, and system design, ensuring public health protection and environmental compliance. This chapter links technical calculations to regulatory frameworks, policy interpretation, and professional practice.

Air quality regulations operate at multiple levels:

- International (WHO guidelines).
- National (e.g., NAAQS, EU Directives).
- Regional and local standards.

Engineers must interpret these standards, evaluate compliance, and design systems to meet or exceed regulatory requirements.

2. Purpose of Air Quality Standards.

Air quality standards translate scientific understanding into enforceable limits to protect human health and the environment. They provide engineers with targets for emission reductions, ventilation, stack design, and dispersion modeling. Standards focus on preventing adverse effects while allowing for practical engineering solutions.

Key objectives:

- Protect public health with a margin of safety.
- Protect sensitive populations such as children and the elderly.
- Prevent environmental and material damage.
- Provide enforceable benchmarks for regulators.

Standards are based on epidemiological evidence rather than the elimination of all risk.

3. Types of Air Quality Standards.

Different types of standards address different goals and exposure durations. Engineers must understand the distinctions to select appropriate compliance metrics and design controls.

3.1 Primary vs Secondary Standards

- Primary standards: Protect human health
- Secondary standards: Protect welfare, including visibility, crops, and ecosystems

3.2 Averaging Time

Pollutant impacts vary depending on the duration of exposure:

- 1-hour (acute effects).
- 8-hour (occupational and health-based).
- 24-hour (short-term).
- Annual (chronic exposure).

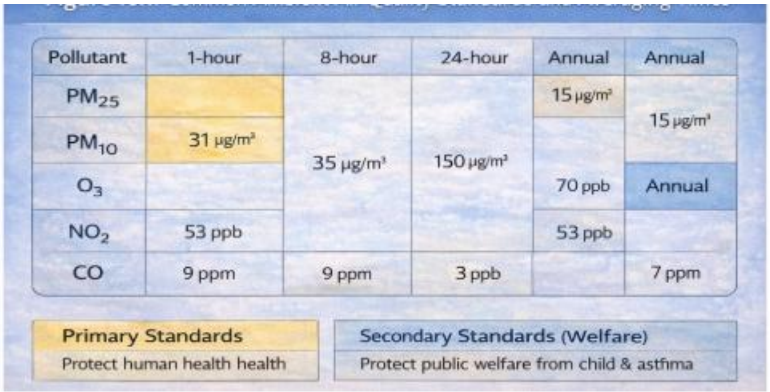
4. Common Ambient Air Quality Standards (Typical Values).

Air quality standards provide numerical limits for major pollutants as listed in Table 9. Engineers use these values as design constraints for emissions control, dispersion calculations, and compliance monitoring.

Table 9: Air Quality Standards

Pollutant	Averaging Time	Limit
$PM_{2.5}$	Annual	15 µg/m³
$PM_{2.5}$	24-hour	35 µg/m³
PM_{10}	24-hour	150 µg/m³
O_3	8-hour	70 ppb
NO_2	Annual	53 ppb
CO	8-hour	9 ppm

Figure 34 summarizes the standards for major pollutants in an easy-to-read table or bar chart format.



Pollutant	1-hour	8-hour	24-hour	Annual	Annual
PM_{25}		35 µg/m³	150 µg/m³	15 µg/m³	15 µg/m³
PM_{10}	31 µg/m³			70 ppb	
O_3					Annual
NO_2	53 ppb			53 ppb	
CO	9 ppm	9 ppm	3 ppb		7 ppm

Primary Standards	Secondary Standards (Welfare)
Protect human health health	Protect public welfare from child & astfima

Figure 33: Common Ambient Air Quality Standards and Averaging Times

Example 1: Compliance Assessment

Measured 24-hour $PM_{2.5}$ concentration = 42 µg/m³; Standard = 35 µg/m³

Solution:
42 > 35 → non-compliant

Engineering implication: Emission controls or operational adjustments are required to achieve compliance.

5. Design Value Concept.

Compliance is determined by statistical design values rather than single measurements. Engineers use these metrics to account for variability and extreme events, ensuring robust protection under fluctuating conditions.

Example ($PM_{2.5}$):

- 98th percentile of 24-hour concentrations.
- Averaged over 3 years.

This approach reduces the influence of short-term fluctuations and allows consistent regulatory enforcement.

6. Air Quality Index (AQI).

The AQI provides a simplified, public-friendly interpretation of pollutant concentrations. Engineers use AQI to communicate air quality risk and to guide operational decisions during periods of high pollution.

AQI categories:

- 0–50: Good.
- 51–100: Moderate.
- 101–150: Unhealthy for sensitive groups.
- 151–200: Unhealthy.
- 201–300: Very unhealthy.
- > 300: Hazardous.

Figure 35 communicates public-friendly AQI scale visually.

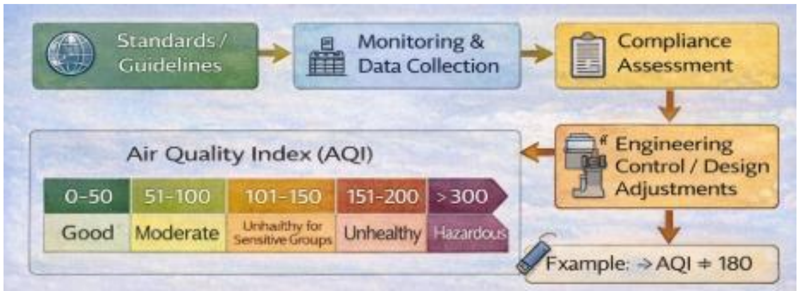


Figure 34: Air Quality Index (AQI) Categories and Health Interpretation

Example 2: AQI Calculation ($PM_{2.5}$)

$PM_{2.5}$ concentration = 110 µg/m³

Using AQI breakpoints:

- 55.5–150.4 µg/m³ → AQI 151–200

Linear interpretation:

Linear interpolation:
$AQI = ((110 - 55.5)/(150.4 - 55.5)) \times (200 - 151) + 151$
$AQI \approx 180$

Interpretation: Air quality is classified as unhealthy.

7. Regulatory Framework and Enforcement.

Air quality management relies on a combination of monitoring, permitting, and enforcement. Engineers support these systems by designing monitoring networks, analyzing data, and optimizing emission control processes to maintain compliance.

Key elements:

- Emission permits.
- Ambient monitoring networks.
- Source testing and reporting.
- Enforcement actions and penalties.

Figure 36 illustrate the link between standards, monitoring, permits, and engineering design decisions.

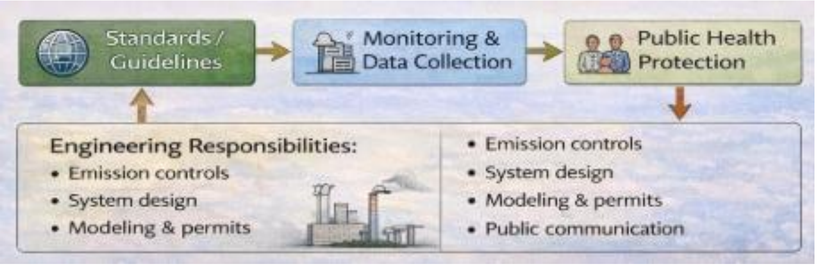


Figure 35: Air Quality Regulatory Framework and Engineering Responsibilities

Example 3: Emission Reduction Requirement

Current PM emission = 120 g/s; Allowed emission = 80 g/s. Calculate the required reduction.

Solution:
Required reduction (%) = $(120 - 80)/120 \times 100 = 33.3\%$

Engineering implication: Control strategies must achieve at least a 33% reduction in emissions.

8. Relationship Between Standards and Engineering Design.

Air quality standards directly influence engineering decisions. Compliance depends on design factors such as:

- Stack height, which affects ground-level concentrations.
- Control device efficiency, which determines emission rates.
- Operating schedules, which influence averaging times.

Designs must consider worst-case meteorological conditions to ensure consistent compliance.

9. International Perspective.

Global engineers must account for variations in air quality regulations. WHO guidelines are often more stringent than local standards, while developing regions may adopt phased compliance schedules. Engineers must adapt designs to meet the applicable local and international regulations.

10. Summary of Engineering Implications.

- Standards define engineering design constraints.
- AQI links technical measurements to public communication.
- Compliance requires integration of monitoring, modeling, and control strategies.
- Engineers play a key role in regulatory decision-making and public health protection.

CHAPTER 11: PARTICULATE MATTER CONTROL DEVICES

1. Introduction.

Particulate matter control is a fundamental aspect of air pollution engineering because fine and coarse particles are closely linked to health effects, visibility reduction, and material degradation. This lecture focuses on the engineering principles, design equations, and performance evaluation of major PM control devices. Engineers must select, size, and integrate these devices to meet regulatory standards efficiently and cost-effectively.

Particulate control devices rely on several physical mechanisms:

- Inertial separation.
- Gravitational settling.
- Filtration.
- Electrostatic attraction.

2. Particle Characteristics Relevant to Control.

Understanding particle properties is essential for designing effective control systems. Factors such as size, density, shape, and electrical properties determine the collection efficiency of different devices. Fine particles ($PM_{2.5}$) are generally more difficult to remove than coarser particles (PM_{10}), which influences device selection and performance evaluation.

Key properties influencing collection efficiency:

- Aerodynamic diameter (µm).
- Particle density.
- Shape and surface properties.
- Electrical resistivity.

The particle size range and applicability of PM control devices is represented in Figure 37.

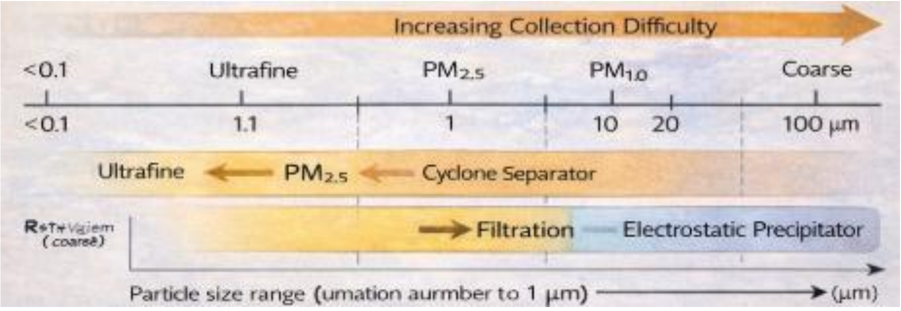


Figure 36: Particle Size Range and Applicability of PM Control Devices

3. Gravity Settling Chambers.

Gravity settling chambers remove particles from gas streams by allowing them to settle under the influence of gravity. Design is governed by the particle settling velocity relative to the residence time in the chamber. Engineers apply Stokes' law for laminar flows to estimate performance.

Design Equation (Stokes' law, laminar flow):

$$v_s = \frac{g d_p^2 (\rho_p - \rho_a)}{18\mu}$$

Where:

- d_p= particle diameter
- ρ_p= particle density
- ρ_a= air density
- μ = air viscosity

The operating principles of major particulate matter control devices are represented in Figure 38.

Figure 37: Operating Principles of Major Particulate Matter Control Devices

Example 1: Settling Velocity

- Particle diameter = 20 µm
- Particle density = 2,000 kg/m³
- Air density = 1.2 kg/m³
- Air viscosity = 1.8×10^{-5} kg/m·s

Solution:

$$v_s = \frac{9.81 \times (20 \times 10^{-6})^2 \times (2000 - 1.2)}{18 \times 1.8 \times 10^{-5}} \approx 0.12 \text{ m/s}$$

Interpretation: Only coarse particles can be effectively removed by gravity settling chambers.

4. Cyclone Separators.

Cyclones remove particles by imparting centrifugal force to the gas stream. As the gas swirls, particles with higher inertia move toward the walls and are collected. Device performance depends on inlet velocity, cyclone diameter, and particle characteristics.

Simplified Collection Efficiency:

$$\eta = 1 - \exp\left(-Stk\right)$$

Where Stk is the Stokes number.

Example 2: Cyclone Efficiency

Stokes number = 2.1. Evaluate the effect of the cyclone.

Solution:

$$\eta = 1 - \exp\left(-2.1\right) = 0.88$$

Result: Cyclone removes 88% of particles of this size.

5. Fabric Filters (Baghouses).

Fabric filters capture particles as gas passes through woven or felted media. Collection occurs via interception, impaction, and diffusion. Baghouse systems are highly efficient and capable of capturing $PM_{2.5}$, but they require careful design to manage pressure drop and fabric degradation.

Filtration Velocity (Air-to-Cloth Ratio):

$$A/C = \frac{Q}{A_f}$$

Where Q = gas flow rate, and A_f = fabric area.

Example 3: Baghouse Sizing

- Gas flow = 40,000 m^3/h
- Design A/C ratio = 1.5 m/min (convert to 90 m/h)

Calculate the fabric area.

Solution:

$$A_f = \frac{40{,}000}{90} \approx 444\ \mathrm{m}^2$$

6. Electrostatic Precipitators (ESPs).

ESPs remove particles by electrically charging them and collecting them on oppositely charged plates. Device efficiency depends on particle migration velocity, plate area, and gas flow rate.

Deutsch–Anderson Equation:

$$\eta = 1 - \exp\left(\frac{wA}{Q}\right)$$

Where:

- w = particle migration velocity (m/s)
- A = collection plate area (m^2)
- Q = gas flow rate (m^3/s)

Example 4: ESP Efficiency

- w = 0.08 m/s
- A = 2,500 m^2
- Q = 50 m^3/s

Evaluate the ESP efficiency.

Solution:

$$\eta = 1 - \exp\left(-0.08 \times 2500/50\right) = 1 - \exp\left(-4\right) \approx 0.982$$

Result: ESP achieves 98.2% efficiency.

7. Pressure Drop and Energy Considerations.

High-efficiency PM control devices often require higher pressure drops, increasing fan power and energy consumption. Engineers must balance collection efficiency with operational costs.

Fan Power Calculation:

$$P = \frac{Q\Delta P}{\eta_{\text{fan}}}$$

A trade-off between collection efficiency, pressure drop, and energy consumption is shown in Figure 39.

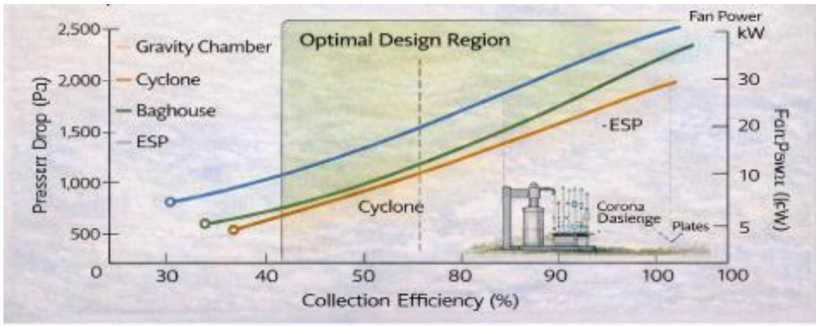


Figure 38:Trade-off between Collection Efficiency, Pressure Drop, and Energy Consumption

Example 5: Fan Power Requirement for a PM Control Device

A fabric filter system treats an exhaust gas flow of 45,000 m³/h. The pressure drop across the control device is 1,200 Pa. The fan operates at an overall efficiency of 65%. Determine the required fan power.

Solution:

Convert volumetric flow rate to m³/s:

$$Q = \frac{45{,}000}{3{,}600} = 12.5\ \text{m}^3/\text{s}$$

Apply the fan power equation:

$$P = \frac{Q\Delta P}{\eta_{\text{fan}}}$$

Substitute values:

$$P = \frac{12.5 \times 1{,}200}{0.65}$$

$$P = \frac{15{,}000}{0.65} \approx 23{,}100 \text{ W}$$

$$P \approx 23.1 \text{ kW}$$

Interpretation:
The particulate control device requires approximately 23 kW of fan power to overcome the pressure drop. Increasing collection efficiency would typically increase pressure drop and energy demand, highlighting the need to balance air quality performance with operating cost during system design.

8. Device Selection Criteria.

Choosing the appropriate PM control device depends on particle characteristics, required efficiency, gas conditions, and economic considerations. Engineers must also consider maintenance and operational reliability.

Factors to consider:

- Particle size distribution.
- Required efficiency.
- Gas temperature and chemistry.
- Capital and operating cost.
- Maintenance requirements.

9. Summary of Engineering Implications.

- PM control uses multiple physical collection mechanisms.
- Device selection must align with particle characteristics and process conditions.
- Numerical design ensures regulatory compliance while minimizing cost and energy use.

CHAPTER 12: GASEOUS POLLUTANT CONTROL TECHNOLOGIES

1. Introduction.

While particulate matter can often be removed using mechanical or electrostatic devices, the control of gaseous pollutants requires processes based on chemical reactions and phase interactions. This chapter examines the engineering foundations of gas-phase air pollution control technologies used to manage sulfur dioxide, nitrogen oxides, volatile organic compounds, and acid gases. Emphasis is placed on understanding pollutant behavior, selecting appropriate control methods, and applying design equations to achieve regulatory compliance in a cost-effective manner.

Common gaseous control strategies include:

- Absorption (wet scrubbers).
- Adsorption (activated carbon).
- Condensation.
- Thermal and catalytic oxidation.

The major gaseous pollutant control technologies and their operating principles are shown in Figure 40.

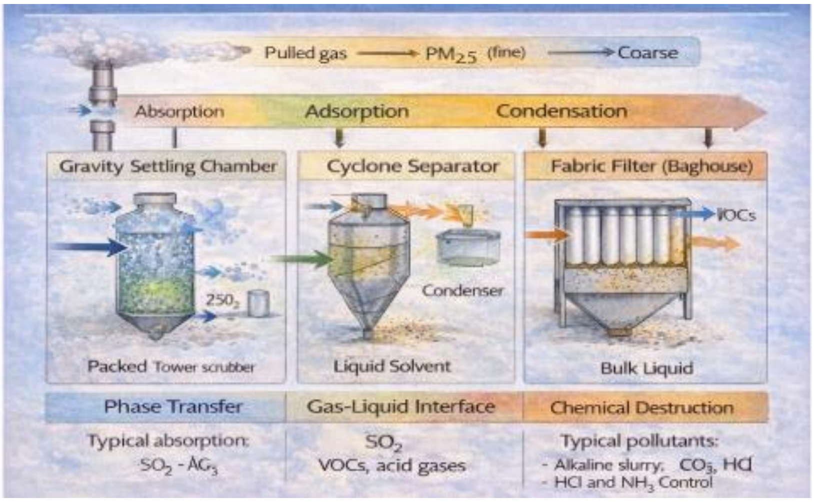


Figure 39: Major Gaseous Pollutant Control Technologies and their Operating Principles

2. Properties of Gaseous Pollutants Relevant to Control.

The selection and performance of gaseous pollutant control systems depend strongly on the physical and chemical properties of the target contaminants. Engineers must evaluate these properties to determine which control mechanism will be effective under given operating conditions. Differences in solubility, reactivity, and volatility often dictate whether a pollutant can be efficiently removed using liquid absorption, surface adsorption, or chemical destruction.

Key properties governing control selection:

- Solubility in liquids (Henry's law constant).
- Chemical reactivity.
- Vapor pressure.
- Concentration and flow rate.
- Temperature and moisture content.

Highly soluble or reactive gases are best treated by absorption, while low-solubility organic compounds are commonly controlled through adsorption or oxidation processes.

3. Absorption (Wet Scrubbers).

Absorption is one of the most widely used techniques for controlling gaseous air pollutants, particularly acid gases. In absorption systems, pollutants are transferred from the gas phase into a liquid solvent, where they may dissolve or react chemically. The effectiveness of this process depends on gas–liquid contact, solubility, and reaction kinetics.

Principle
Absorption removes gaseous pollutants by dissolving them into a liquid solvent, usually water or an alkaline solution. The process is governed by mass transfer across a gas–liquid interface.

Typical applications:

- SO_2 removal using alkaline slurry.
- HCl and HF control.
- Ammonia removal.

The gas–liquid mass transfer in an absorption (wet scrubber) system is represented in Figure 41.

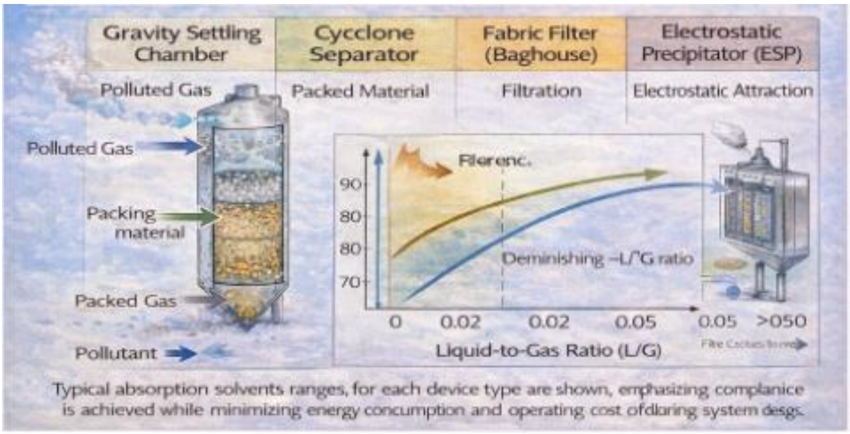


Figure 40:Gas–Liquid Mass Transfer in an Absorption (Wet Scrubber) System

3.1 Henry's Law

Gas solubility is a critical parameter in absorption system design. Henry's Law relates the concentration of a dissolved gas in a liquid to its partial pressure in the gas phase. This relationship allows engineers to estimate how readily a pollutant can be absorbed under equilibrium conditions.

$$C_l = H \times P_g$$

Where:

- C_l = dissolved concentration (mol/m³)
- P_g = partial pressure (atm)
- H = Henry's law constant

Lower values of H indicate higher solubility and generally more efficient absorption.

Example 1: Gas Solubility

SO_2 partial pressure = 0.002 atm, Henry's constant = 1.2 mol/m³·atm.

Calculate the dissolved concentration (mol/m³).

$$C_l = 1.2 \times 0.002 = 0.0024 \text{ mol/m}^3$$

Interpretation:
SO_2 exhibits high solubility in water, making it well-suited for removal using wet scrubber systems.

4. Scrubber Efficiency.

The effectiveness of an absorption system is commonly expressed in terms of removal efficiency. This metric quantifies the fraction of pollutant removed as gas passes through the scrubber and provides a basis for regulatory compliance assessment.

Overall removal efficiency:

$$\eta = \frac{C_{in} - C_{out}}{C_{in}}$$

Scrubber performance depends on:

- Gas–liquid contact area.
- Liquid-to-gas ratio (L/G).
- Reaction kinetics.

Example 2: Scrubber Removal Efficiency

- Inlet SO_2 = 800 ppm
- Outlet SO_2 = 80 ppm

Calculate the overall removal efficiency.

$$\eta = \frac{800 - 80}{800} = 0.90 = 90\%$$

5. Packed Tower Scrubber Design.

Packed tower scrubbers are designed to maximize contact between the gas and liquid phases by introducing packing materials that increase surface area. These systems are widely used for continuous, high-efficiency gas absorption applications.

Packed towers increase contact area using structured or random packing.

Key design parameter:

Liquid-to-gas ratio (L/G) (m^3 liquid / m^3 gas).

Higher L/G ratios generally improve pollutant removal but also increase pumping energy and operating costs. The packed tower scrubber showing the gas–liquid contact and the effect of L/G ratio is represented in Figure 42.

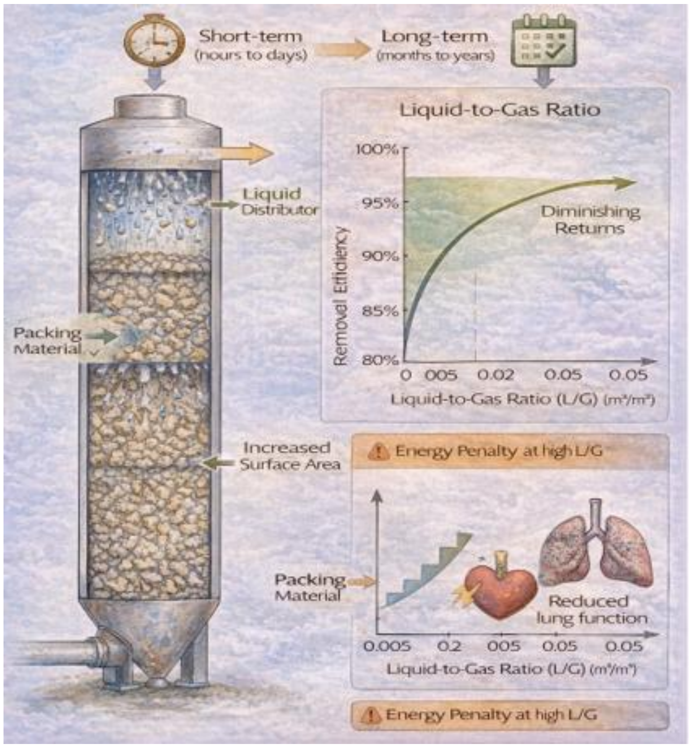


Figure 41: Packed Tower Scrubber Showing Gas–Liquid Contact and Effect of L/G Ratio

Example 3: Liquid Flow Rate

- Gas flow rate = 10,000 m³/h
- Design L/G = 0.005

Calculate L.

$$L = 10{,}000 \times 0.005 = 50 \text{ m}^3/\text{h}$$

6. Adsorption Systems.

Adsorption systems are used when gaseous pollutants are poorly soluble in liquids or present at relatively low concentrations. In these systems, pollutants adhere to the surface of a solid adsorbent, most commonly activated carbon.

Principle
Adsorption removes gaseous pollutants by binding molecules onto a solid surface.

Applications:

- VOC control
- Odor removal
- Low-concentration pollutants

Adsorption Capacity

$$q = \frac{(C_{in} - C_{out})Qt}{m_c}$$

Where m_c is the mass of adsorbent.

Example 4: Activated Carbon Requirement

- VOC inlet = 200 mg/m³
- VOC outlet = 20 mg/m³
- Gas flow = 5,000 m³/h
- Operation time = 10 h
- Carbon capacity = 0.25 kg VOC/kg carbon

Calculate the mass of adsorbent.

Solution

Mass removed:

$$m = (200 - 20) \times 5{,}000 \times 10 \times 10^{-6} = 9 \text{ kg VOC}$$

Carbon required:

$$m_c = \frac{9}{0.25} = 36 \text{ kg}$$

7. Thermal and Catalytic Oxidation.

Oxidation systems destroy gaseous organic pollutants rather than transferring them to another phase. These technologies are especially effective for high-concentration VOC streams where recovery is not practical.

Principle

Organic gases are oxidized to carbon dioxide and water.

- Thermal oxidizers: High temperature (700–1,200°C).
- Catalytic oxidizers: Lower temperature (300–500°C).

Figure 43 shows the comparison of adsorption and oxidation control mechanisms.

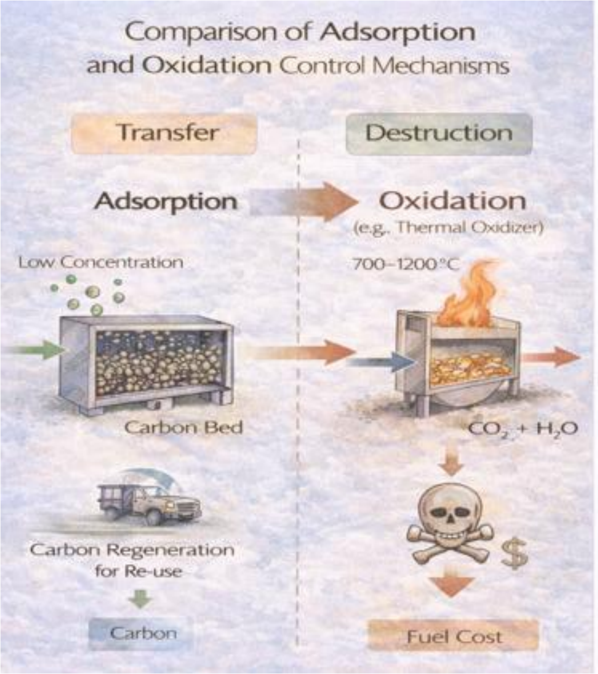


Figure 42: Comparison of Adsorption and Oxidation Control Mechanisms

Example 5: Destruction Efficiency

VOC inlet = 1,500 ppm
VOC outlet = 15 ppm

Calculate the destruction efficiency.

$$\eta = \frac{1500 - 15}{1500} = 99\%$$

8. Technology Selection Guidelines.

Selecting an appropriate gaseous control technology requires balancing pollutant characteristics, efficiency requirements, energy consumption, and cost. Table 6 summarizes common matches between pollutants and preferred control methods.

Table 10: Pollutants and Preferred Control Methods

Pollutant	Preferred Technology
SO_2	Wet scrubber
HCl/HF	Absorption
VOCs (low conc.)	Adsorption
VOCs (high conc.)	Oxidation
Odors	Carbon adsorption

9. Summary of Engineering Implications.

Gas-phase air pollution control relies on a combination of chemical equilibrium, mass transfer, and reaction engineering principles. Proper system selection and design are essential to achieving regulatory compliance while minimizing energy use and operational cost.

- Gas-phase control relies on chemical and mass transfer principles.
- Proper selection ensures compliance and energy efficiency.
- Numerical design prevents under- or over-design.

CHAPTER 13: AIR POLLUTION AND CLIMATE CHANGE

1. Introduction.

Air pollution and climate change are closely linked environmental challenges that share common sources, atmospheric processes, and mitigation strategies. Many air pollutants influence Earth's radiation balance either directly, by absorbing or reflecting energy, or indirectly, by affecting cloud formation and atmospheric chemistry. At the same time, changes in climate alter meteorological conditions that govern pollutant formation, transport, and removal. For engineers, understanding these interactions is essential for designing systems that protect air quality while supporting long-term climate mitigation goals.

This chapter examines:

- Greenhouse gases (GHGs) and short-lived climate pollutants (SLCPs).
- Radiative forcing and climate impact metrics.
- CO_2-equivalent emissions and Global Warming Potential.
- Engineering tradeoffs between air quality control and climate objectives.

Figure 44 illustrates the interconnected nature of air pollution and climate change, emphasizing the feedback mechanisms and tradeoffs discussed throughout this chapter.

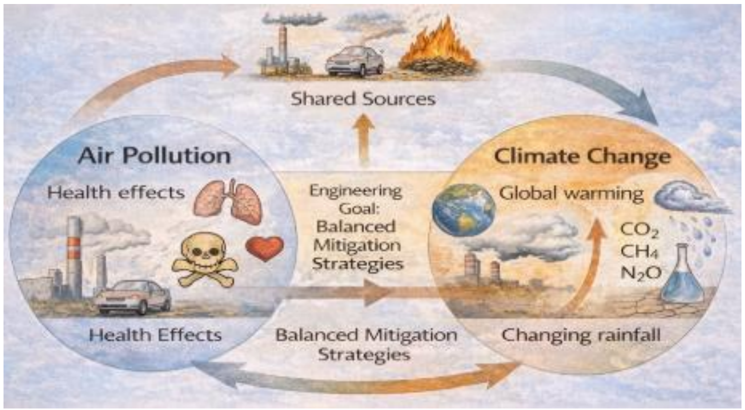


Figure 43: Interconnections Between Air Pollution and Climate Change

2. Greenhouse Gases and Short-Lived Climate Pollutants.

Atmospheric pollutants vary widely in their ability to influence climate depending on their chemical properties, radiative behavior, and atmospheric lifetime. This section distinguishes between long-lived greenhouse gases and short-lived climate pollutants, both of which contribute to warming but over different time scales. Understanding these differences helps engineers prioritize control strategies based on desired climate outcomes.

2.1 Major Greenhouse Gases

Greenhouse gases are long-lived compounds that trap outgoing infrared radiation, leading to sustained warming of the atmosphere. Their cumulative impact depends on emission rates and persistence over decades to centuries.

Major greenhouse gases include:
- Carbon dioxide (CO_2).
- Methane (CH_4).
- Nitrous oxide (N_2O).
- Fluorinated gases.

2.2 Short-Lived Climate Pollutants (SLCPs)

Short-lived climate pollutants have much shorter atmospheric lifetimes but often exert strong warming effects while present. Reducing these pollutants can yield rapid climate and public health benefits.

Key SLCPs include:
- Black carbon (BC).
- Tropospheric ozone (O_3).
- Methane (also classified as a GHG).

SLCPs have high warming potential but short atmospheric lifetimes, offering opportunities for near-term climate mitigation.

3. Atmospheric Lifetime and Climate Impact.

The climate influence of an air pollutant depends not only on its radiative properties but also on how long it remains in the atmosphere. Pollutants with long lifetimes accumulate and drive long-term warming, while short-lived species can cause intense but temporary effects. Engineers must recognize these distinctions when evaluating emission reduction strategies. Pollutants with expected lifetime and climate effects are presented in Table 7.

Table 11: Pollutant/Lifetime/Climate Effect

Pollutant	Lifetime	Climate Effect
CO_2	100+ years	Long-term warming
CH_4	~12 years	Strong warming
Black carbon	Days–weeks	Strong warming
SO_2 aerosols	Days	Cooling (indirect)

Reducing some air pollutants, such as SO_2, may inadvertently increase warming by removing cooling aerosols, highlighting the need for integrated assessment.

4. Radiative Forcing Concept.

Radiative forcing provides a quantitative framework for evaluating how pollutants alter Earth's energy balance. It represents the difference between incoming solar radiation and outgoing infrared radiation and serves as a central metric in climate science.

$$\text{RF} = \text{Incoming solar} - \text{Outgoing infrared} \ (\text{W/m}^2)$$

- Positive radiative forcing → warming
- Negative radiative forcing → cooling

Greenhouse gases increase radiative forcing by reducing the amount of infrared radiation escaping to space. Figure 45 illustrates how different atmospheric constituents modify Earth's energy balance and produce positive or negative radiative forcing.

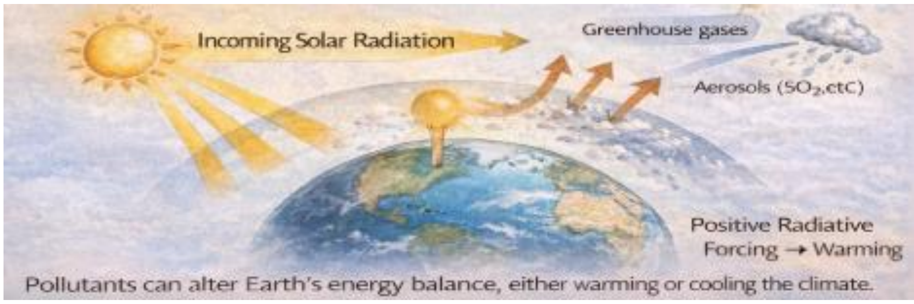


Figure 44: Conceptual Illustration of Radiative Forcing in the Earth–Atmosphere System

5. Global Warming Potential (GWP).

Because different gases vary in their warming strength and atmospheric lifetime, direct comparison requires a common metric. Global Warming Potential expresses the climate impact of a pollutant relative to carbon dioxide over a specified time horizon, most commonly 100 years as shown in Table 12.

Table 12: Global Warming Potential for Gas

Gas	GWP_{100}
CO_2	1
CH_4	28
N_2O	265

GWP allows engineers and policymakers to compare emissions across different pollutant types using a single scale.

Example 1: CO_2-Equivalent Emissions

This example demonstrates how Global Warming Potential is applied to convert emissions of a non-CO_2 gas into carbon dioxide equivalents.

A facility emits 2 tons of CH_4 per year. Calculate CO_2-equivalent emissions.

$$CO_2\text{-e} = 2 \times 28 = 56 \text{ tonnes } CO_2\text{-e/year}$$

Interpretation:
Controlling methane emissions can provide substantial climate benefits relative to the mass emitted.

6. Air Quality–Climate Interactions.

Air quality management and climate mitigation are tightly interconnected. Some pollutants affect both human health and climate, while climate change itself alters the conditions under which air pollution forms and persists. Engineering solutions must therefore evaluate both dimensions simultaneously.

6.1 Ozone

Tropospheric ozone is unique in that it functions as both a regulated air pollutant and a greenhouse gas.

- O_3 contributes to warming.
- Higher temperatures accelerate ozone formation reactions.

6.2 Particulate Matter

Particles influence climate in different ways depending on composition.

- Sulfate aerosols produce a cooling effect.
- Black carbon causes warming and severe health impacts.

Figure 46 summarizes the operating principles of major particulate matter control devices, which influence both air quality and climate by altering particle mass, size distribution, and chemical composition.

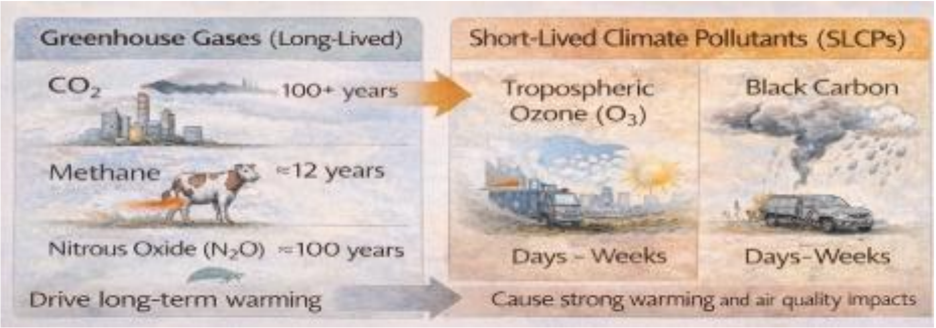


Figure 45: Operating Principles of Major Particulate Matter Control Devices

Engineering controls must assess net climate effects rather than focusing on air quality alone.

Example 2: Black Carbon Mitigation Benefit

This example illustrates the climate benefit of reducing emissions of a high-impact short-lived pollutant.

Black carbon emissions reduced by 0.5 tons/year. Assume BC $GWP_{100} \approx 900$, calculate the CO_2-e reduction per year.

$$CO_2\text{-e reduction} = 0.5 \times 900 = 450 \text{ tonnes } CO_2\text{-e/year}$$

7. Climate Change Effects on Air Pollution.

Climate change modifies meteorological and atmospheric conditions that govern air pollution behavior. These changes can worsen pollution episodes and challenge existing control strategies.

Climate change influences air quality by:

- Increasing stagnation events.
- Enhancing photochemical smog formation.
- Altering precipitation and pollutant removal.
- Increasing wildfire frequency and particulate emissions.

Engineers must design air quality systems that remain effective under future climate conditions.

8. Engineering Co-Benefits and Tradeoffs.

Many engineering interventions affect both air quality and climate, sometimes in complementary ways and sometimes in conflict. Evaluating these interactions is essential for sustainable design.

Co-Benefits:

- Energy efficiency reduces CO_2 and criteria pollutants.
- Electrification lowers NO_x and PM emissions.

Tradeoffs:

- Scrubbers increase energy consumption.
- Aerosol reductions may reduce atmospheric cooling.

Life-cycle assessment (LCA) is a critical tool for evaluating these tradeoffs.

Example 3: Energy Penalty and CO_2 Emissions

This example highlights the climate implications of energy-intensive pollution controls.

Scrubber increases power consumption by 500 MWh/year, the emission factor = 0.6 t CO_2/MWh. Calculate the additional CO per year.

$$\text{Additional } CO_2 = 500 \times 0.6 = 300 \text{ t } CO_2/\text{year}$$

This increase must be weighed against SO_2 reduction and public health benefits to determine net impact.

9. International Climate Policy Context.

Air pollution and climate engineering decisions operate within an evolving global policy framework. Engineers play a key role in translating international agreements into practical technologies.

Key elements include:

- Paris Agreement goal of limiting warming to below 2°C.
- Nationally Determined Contributions (NDCs).
- Technology deployment and emissions reporting.

10. Summary of Engineering Implications.

This chapter underscores the need for integrated approaches to air quality and climate challenges.

- Air pollution control and climate mitigation are interconnected.
- GWP enables comparison across pollutants.
- SLCP reductions deliver rapid climate and health benefits.
- Engineering decisions must account for long-term climate impacts.

CHAPTER 14: INTEGRATED AIR POLLUTION CASE STUDIES AND SYSTEM-LEVEL DESIGN

1. Introduction.

This chapter integrates dispersion modeling, emissions control, regulatory compliance, cost analysis, and energy considerations into realistic, system-level air pollution engineering case studies reflective of professional practice.

This chapter also synthesizes the entire course by applying integrated engineering analysis to real-world air pollution problems. Practicing engineers must combine emissions estimation, dispersion modeling, control technology selection, health and regulatory constraints, economic feasibility, and energy considerations into coherent, defensible system-level solutions. This lecture emphasizes engineering judgment, transparent assumptions, and tradeoff analysis consistent with professional practice and accreditation expectations.

Learning objectives:

- Integrate multiple air pollution analysis tools into a single decision framework.
- Evaluate technical, economic, and regulatory tradeoffs quantitatively.
- Produce professional-quality engineering justifications.

2. Integrated Engineering Design Framework.

This section establishes the structured methodology used by practicing air quality engineers to move from problem identification to defensible regulatory compliance decisions. Rather than treating emissions estimation, dispersion modeling, and control selection as isolated tasks, the framework emphasizes logical sequencing, documentation, and iterative refinement. The workflow reflects standard practice in permit applications, environmental impact assessments, and compliance demonstrations, ensuring that technical decisions are traceable, reproducible, and aligned with regulatory expectations.

A flow diagram showing emissions estimation → dispersion modeling → control selection → compliance checking → cost/energy analysis → iteration and documentation is shown in Figure 47.

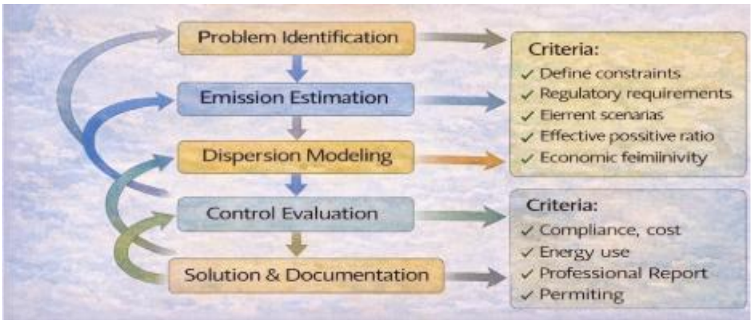


Figure 46: Integrated System-Level Air Pollution Engineering Design Framework

3. Case Study 1: Industrial Stack Compliance ($PM_{2.5}$ and SO_2).

This case study applies the integrated design framework to a realistic industrial emissions scenario involving both particulate and gaseous pollutants. Fuel-oil-fired boilers are common sources subject to stringent air quality standards, making them well suited for illustrating screening dispersion analysis, control technology evaluation, and compliance determination. The example highlights how engineers assess exceedances, compare control efficiencies, and justify technology selection using quantitative criteria.

A schematic linking emission rates, dispersion modeling, PM and SO_2 control technologies, and compliance decisions is shown in Figure 48.

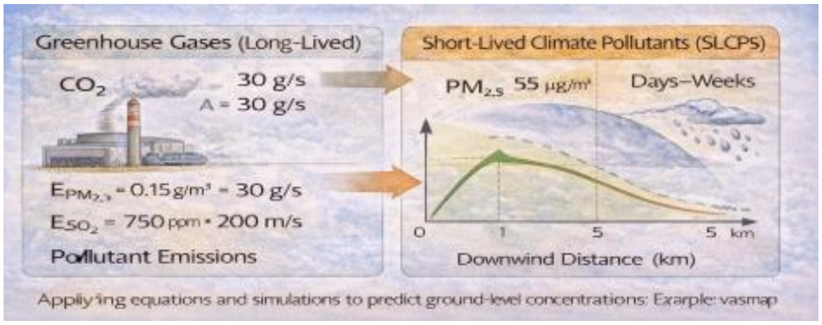


Figure 47: Integrated Compliance Assessment Workflow for an Industrial Point Source

Step 1: Dispersion Screening Using the Gaussian Plume Model

This step demonstrates the use of screening-level dispersion models to rapidly estimate downwind pollutant concentrations under representative meteorological conditions. Gaussian plume modeling is widely accepted for preliminary compliance assessments and conservative evaluations, particularly when refined modeling is not yet warranted. The intent is to determine whether emissions have the potential to exceed standards and therefore require control or further analysis.

Step 2: $PM_{2.5}$ Concentration Calculation

In this step, the screening dispersion equation is applied numerically to estimate ground-level particulate concentrations at the nearest sensitive receptor. The calculation illustrates how emission rate, wind speed, atmospheric dispersion parameters, and stack height interact to influence ambient air quality. Results are compared directly with regulatory standards to determine compliance status and the need for mitigation.

Step 3: PM Control Technology Evaluation

This step evaluates feasible particulate control options using removal efficiency as the primary performance metric. Common industrial controls such as cyclones and fabric filters are compared to illustrate how incremental improvements in efficiency translate into large reductions in ambient concentration. The analysis reinforces the importance of selecting controls based on required performance rather than nominal capability alone.

Figure 49 represents a bar or schematic comparison showing uncontrolled emissions, cyclone control, and fabric filter control relative to the air quality standard.

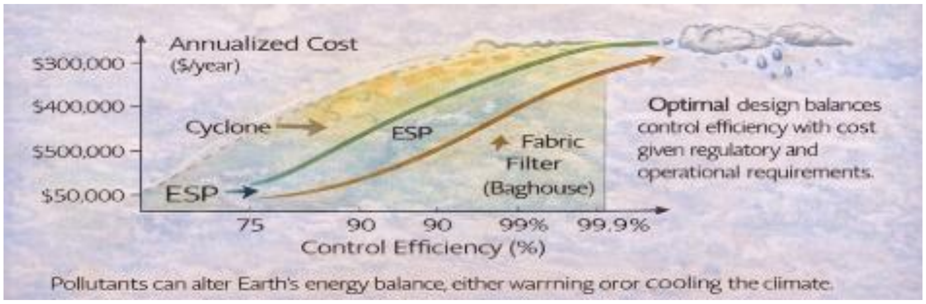


Figure 48: Effect of Particulate Control Efficiency on Ground-Level $PM_{2.5}$ Concentrations

Step 4: SO_2 Control Requirement

This step extends the analysis to gaseous pollutant control, demonstrating how dispersion results and regulatory limits are used to back-calculate required removal efficiency. The example illustrates proportional scaling between pollutants and emphasizes that compliance often requires simultaneous consideration of multiple contaminants. Wet scrubbing is introduced as a representative technology commonly applied to sulfur dioxide control.

4. Case Study 2: Urban Traffic Corridor (NO_2 and $PM_{2.5}$).

This case study shifts focus from point sources to mobile-source-dominated urban environments, where cumulative emissions and exposure patterns are critical. Traffic corridors present complex air quality challenges due to high population density and limited control options. The example demonstrates how combined mitigation strategies are evaluated collectively rather than in isolation to assess their overall effectiveness.

5. Case Study 3: Indoor–Outdoor Air Quality (School).

This section addresses the interaction between outdoor air pollution and indoor exposure, emphasizing the importance of ventilation and filtration in sensitive environments such as schools. Engineers frequently evaluate indoor air quality as part of holistic exposure assessments, particularly where vulnerable populations are present. The case study illustrates how outdoor concentrations, infiltration, and control measures combine to determine indoor pollutant levels.

6. Cost and Energy Tradeoff Analysis.

This section introduces economic and energy considerations as essential components of engineering decision-making. Compliance solutions must be technically effective, financially feasible, and operationally sustainable. By annualizing capital and operating costs, engineers can compare alternatives on a consistent basis and justify selections within budgetary and energy-use constraints.

7. Uncertainty and Safety Factors.

This section highlights the role of uncertainty in air quality engineering and the need for conservative design practices. Variability in meteorology, emissions, and model assumptions necessitates the use of safety factors to ensure continued compliance under adverse conditions. Professional judgment is emphasized as a key element in managing uncertainty responsibly.

8. Professional Documentation.

This section emphasizes that technical correctness alone is insufficient without clear and defensible documentation. Regulatory agencies and stakeholders rely on transparent calculations, stated assumptions, and logical justification to evaluate engineering decisions. Proper documentation supports regulatory approval, legal defensibility, and professional accountability.

9. Summary of Engineering Lessons.

This section synthesizes the key technical and professional insights gained from the integrated case studies. It reinforces the necessity of combining modeling, control design, economics, and regulatory awareness into a unified approach. The lessons reflect core competencies expected of practicing environmental and air quality engineers.

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