GENERAL IDEAS (THEORY) IN AIR POLLUTION CONTROL

1. Alternatives

If we have an air pollution problem we have three control options available:

I. Improve Dispersion to Atmosphere
II. Pollution Prevention (Reduce Emissions)
III. Installation of Downstream Control Devices

I. Improve Dispersion

1) If the dose-response curves indicate that a pollutant has a *threshold value,* then we can remedy the problem if we can improve the dispersion of our emissions and thereby lower the concentrations to which people are exposed to less than that threshold value.

2) 60 years ago, this was the most widely used approach to pollution problems (air or water), *even in industrialized wealthy countries*: *Dilution is the solution to pollution!*

3) This approach is no longer valid because of increased population density. *It may be a solution where applicable* - Accumulation is the key word.

I. Improve Dispersion

Basic idea

Improving the dispersion of our emission,

and thereby,

diluting the pollutants and

lower the concentration near the ground level

where people often exist .

I. Improve Dispersion

- In a sparely populated area, the pollutant emissions are eliminated by natural removal mechanisms and without causing any damage to the neighbors.

- In a densely populated world, dispersion is not a satisfactory approach .

For example

The population density is 1 person/km^2

The population density is 29,000 persons/km^2

I. Improve Dispersion

① Tall stack

The ground-level concentration (z = 0)

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

$$H = h + \Delta h$$

h ↑ ⟹ **H** ↑ ⟹ **c** ↓

1. Improve Dispersion

① Tall stack

- Pro:
  - Raising the stack height, lowers all ground level concentrations near the plant (stack).
  - Downwash is not likely to occur
  - Higher plume height, higher wind speeds (*to drive plume*) thus more dilution.
- Con:
  - However, tall stacks may increase the concentrations at long distances.
  - Concentrations are certainly increased compared to those that would be observed if the emissions were reduced at the source.
  - *Shifting the problem to somewhere else.*

I. Improve Dispersion

① Tall stack

For example: **Acid-rain controversy**

- SO_2 ultimately comes to ground , mostly with rain or snow for away the tall stack.
- Raising the emission point of stack, may raise the concentration far downwind.
- Not solving problem but transferring it to somewhere else.

Power Plant Emissions (Moscow-1984)

Effect of Tall Stacks

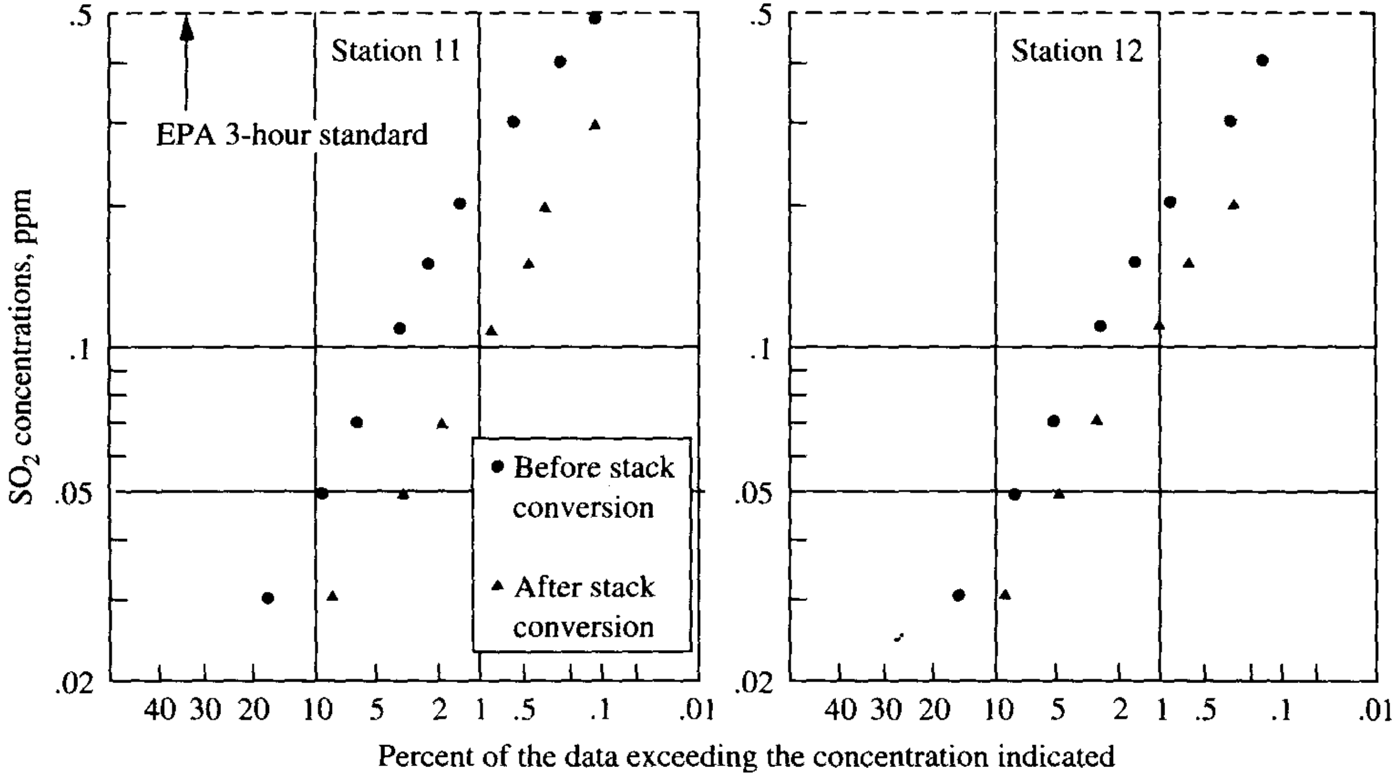
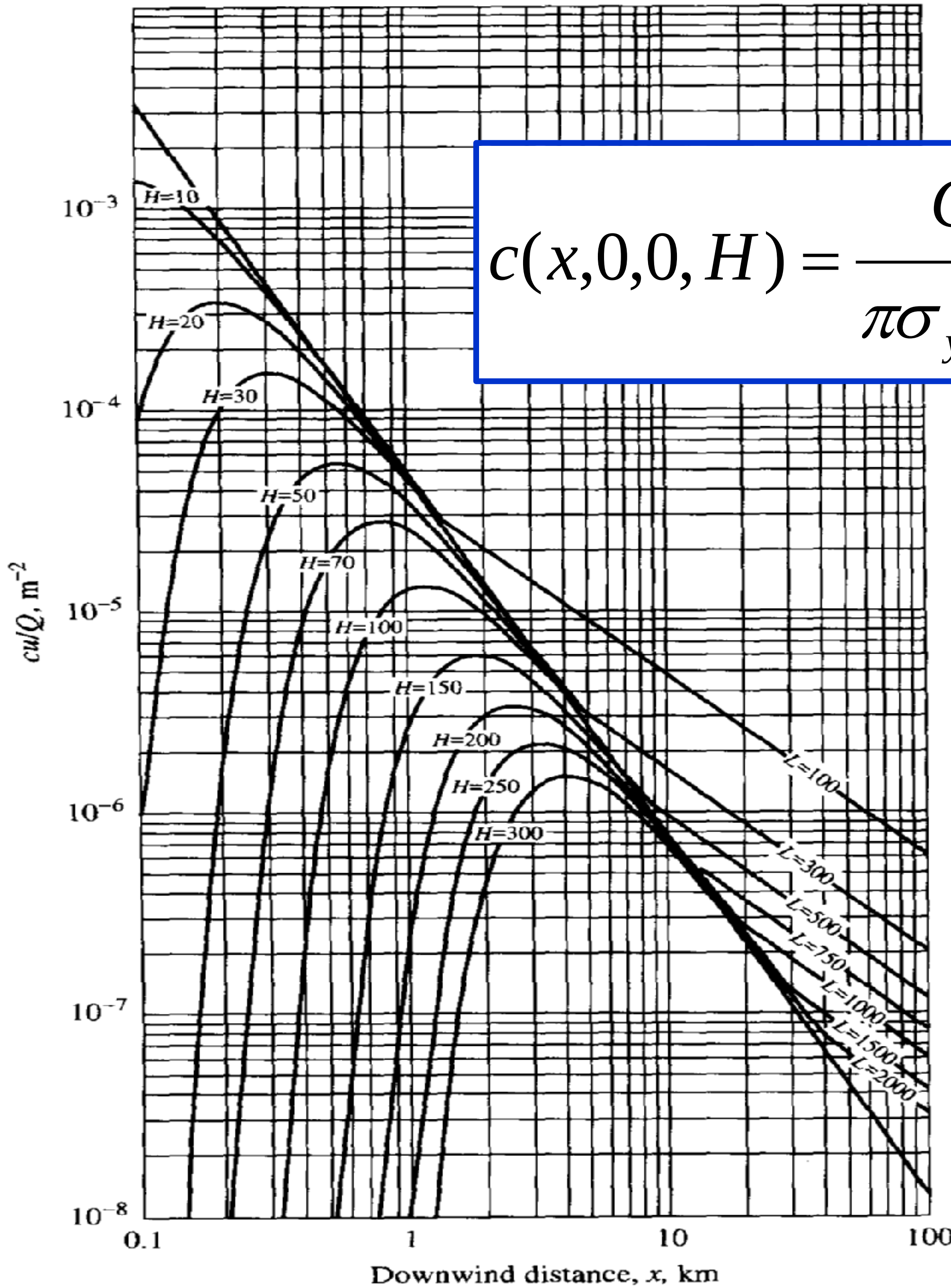


FIGURE 7.1

Comparison of observed hourly sulfur dioxide concentrations at two monitoring stations near a coal-fired power plant, before and after replacement of five short stacks (83 to 113 m) with one tall stack (251 m). Station 11 is 5.3 km southeast of the plant and station 12 is 4.4 km north-northeast of the plant. (From Ref. 1.)

Ground Level Conc. c.u/Q



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

FIGURE 6.9
Ground-level cu/Q, directly under the plume centerline, as a function of downwind distance from the source and effective stack height, H, in meters, *for C stability only.* (From Turner [7].) Here L is the atmospheric mixing height, also in meters.

1. Improve Dispersion

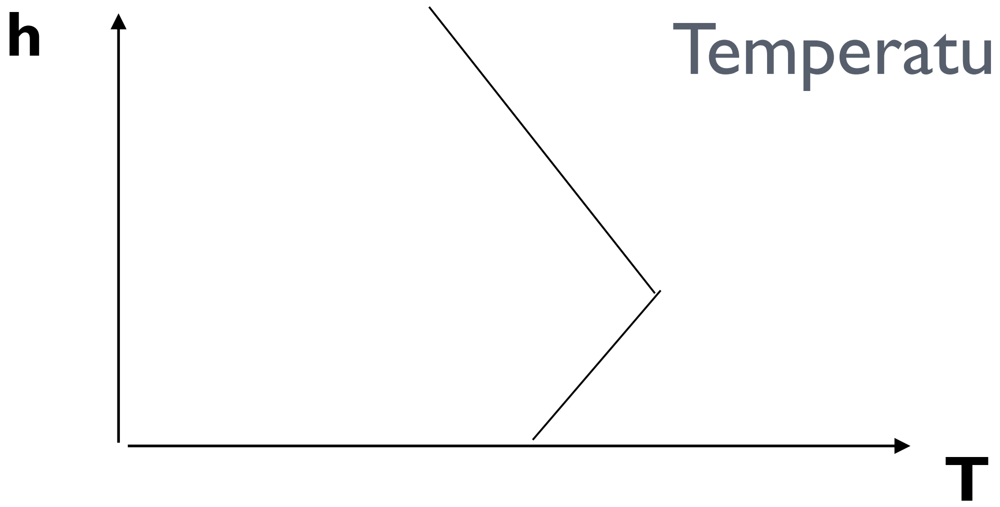
② Intermittent control schemes

- At certain *times of the year (or times of the day),* emissions are more likely to come to ground in high concentrations and in populated areas than at other times.
- Intermittent Control Schemes attempt to reduce emissions during critical times and then allowing them to return to normal rates at other times.
- In most cases, this is achieved by
  1. plant shutdown.
  2. fuel switching.
  3. production curtailment (cut/reduce).
- Intermittent control operates *in addition to* controls that reduce emissions all the time.

I. Improve Dispersion

② Intermittent control schemes

A) Predictive control system



Before 9:00 a.m.

- **Shut off the production**
- **Stringent control of stack emission.**

I. Improve Dispersion

② Intermittent control schemes

B) Observational control system

Ex. 1:

- Mountain communities having large numbers of homes heated with wood stoves may have a public notice system that works when the PM_{10} concentration exceeds some value.
- When this public notice is heard, all wood-burning appliances must be shut off (pure observational case)

I. Improve Dispersion

② Intermittent control schemes

B) Observational control system

Ex. 2:

- High CO concentrations are observed in many U.S. cities in the winter months.
- Therefore, current U.S. federal regulations require the use of oxygenated motor fuels (only during that part of the year in which high ambient CO concentrations are expected) to reduce the motor vehicle CO emissions.
- This is a case that started by observation and operated later on by prediction.

1. Improve Dispersion

3 Relocate the Plant

- A new plant can be located where its emissions will have their **greatest impact in non-populated areas.**
- This reasoning is the basis for most industrial zoning and land-use planning regulations.
  - The zoning generally let poor people live near the pollution-generating industries, but not the rich.
- If a region has a severe current problem with some pollutant, we will generally **not allow a new source of that pollutant** to locate in that region, even if it has the best available controls:
  1. Even a well-controlled new source could add to the current problem.
  2. Instead we will try to locate the plant where any problem with that pollutant is less severe.
- **For new plants:**
  1. Locating far from populated areas
  2. Environmental impact assessment needed.

REMEBER

Improving dispersion is not allowed as a substitute for industrial emission reduction.

II. Pollution Prevention *(P2)*

- There are many examples in which the most economical air pollution control solution done by **process Modification.**
  - Some factories that apply large quantities of paint to their products (e.g., automobiles, refrigerators) have been required to limit the emission of hydrocarbon solvents (paint thinners)
  - Other factories found that they could substitute water-based paints for some of their oil-based paints and greatly reduce their hydrocarbon emissions problem.
  - Open burning of municipal or industrial waste is normally smoky and sooty.
    - Most air pollution control regulations now require that such burning be carried out in closed incinerators, which have much better fuel-air mixing and heat conservation than open burning.
    - The resulting emissions are much less than from open burning of similar wastes.

II. Pollution Prevention *(P2)*

- **Process Modification** also include <u>Switching fuels</u> toreduce emissions.
  - The biggest improvement in air pollutant concentrations in most cities in industrialized countries came about when coal was replaced by natural gas as a home and business heating fuel.
  - Switching vehicles from gasoline to compressed natural gas, propane or ethanol greatly reduces the vehicles’ air pollutant emissions.
- Adding oxygenated compounds to motor fuels (2% oxygen by wt.) lowers CO emissions significantly.
- Requiring the use of low-sulfur fuels reduces sulfur dioxide emissions.

II. Pollution Prevention *(P2)*

- Getting people to carpool, to ride buses or bicycles, or to walk to work is a form of ***process change.***
  - If the process is "get people from home to work," then changing from the one-passenger auto to any of these alternatives is a process change that reduces emissions from the process.

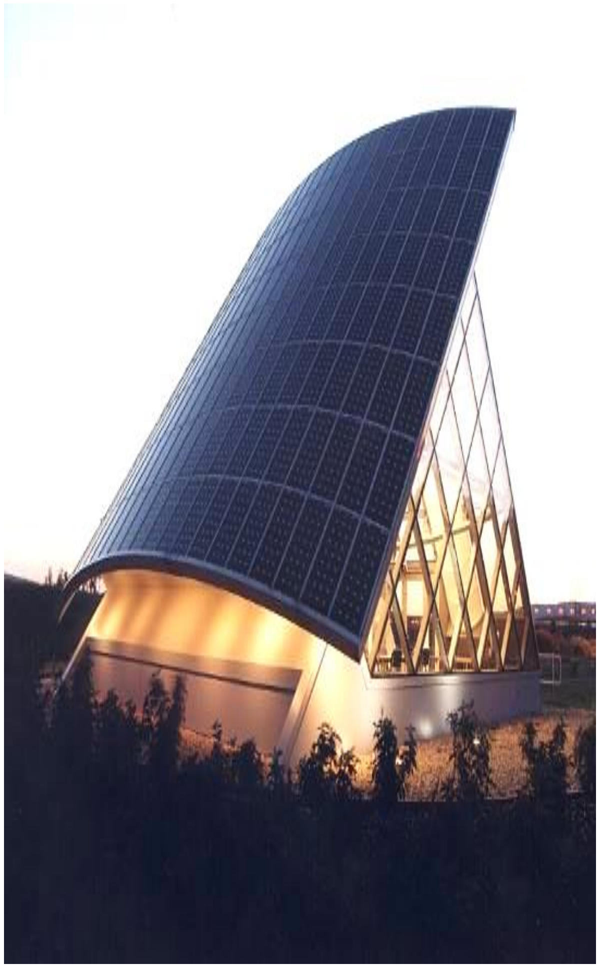
II. Pollution Prevention *(P2)*

- Replacing low-efficiency incandescent lights with higher-efficiency fluorescent lights is a *process change* that reduces emissions.
  - The process is "provide some amount of light"; fluorescent lamps require less electricity for the same amount of light, so less fuel is burned in power plants, and hence less air pollutants are emitted at the plant that produces the electricity.

Money Isn't All You're Saving

II. Pollution Prevention *(P2)*

- In general, any process change in any industry that reduces the consumption of fuels or other raw materials reduces air pollutant emissions, because the production, distribution and use of raw materials and fuels all produce air pollutant emissions; i.e. ***GREEN TECHNOLOGY.***



P2 *Substitution*

Examples of substitution include:

1. Use of N-methyl pyrrolidone (NMP) as an alternative for methylene chloride-based paint strippers:
    - NMP is less toxic and less volatile than methylene chloride.
2. Use of reformulated gasoline (introduced in 1995, mandated in areas where toxins in the air are a constant problem; it contains oxygen-rich chemicals in lesser concentrations than the winter oxygenated gasoline and is formulated to reduce certain toxic chemicals found in conventional and winter oxygenated fuels).
3. Use of **hydro**chlorofluorocarbons (HCFC) and **hydro**fluorocarons (HFCs) for ***chlorofluorocarbons.***

P2Equipment Changes

A variety of process **equipment changes** can be used to reduce pollutant emissions.

These may include:

1. Use of completely enclosed vats in place of open vats where solvent emissions may occur,
2. Replacing leaky oven doors with state-of-the-art seals,
3. Use of flexible doors.

P2 Maintenance

- Performance of equipment (producing products and releasing contaminants to the environment) may be comprised by inadequate maintenance.
  - This is true for process and pollution control equipment.

- **Maintenance** is important in cases below:
  1. In combustion equipment to keep them in good operating condition.
  2. To reduce leakage of solvents and other chemicals from vats, valves, and transmission lines.
  3. To reduce spill-related emissions.

P2Plant Operating Practices

- Excess production of pollutants or emissions may occur as a result of poor equipment and plant operation, particularly in operating boilers and other combustion equipment.

Good boiler and incinerator operation requires:

1. Use of an adequate supply of combustion air.
2. Insufficient combustion air results in incomplete combustion and production of particulate matter (PM) and a variety of gas-phase substances.
3. Good operating practices are important in achieving emission reductions that pollution control equipment is designed for.

P2Process Changes

- Emissions in many cases are related to **processes** used in product manufacturing.
- Emissions of solvent vapors, *for example*, can be reduced in painting operations by dry powder painting.
  1. This technique sprays specially formulated thermoplastic / thermosetting, heat-fusible powders on metallic surfaces which are subsequently heat cured.
  2. Dry powder painting can also be done electro-statically.
  3. In either case, significant reductions in hydrocarbon (HC) emissions can be achieved.

P2Energy Conservation -1

- Reduction in energy use by the application of a variety of energy conservation measures can result in significant emission reductions at various levels.
- All fuels when combusted or partially combusted produce byproducts which pollute the atmosphere.
- Any measure which reduces energy consumption associated with fossil fuel use will result in both a reduction in fuel use and associated emissions.

P2 Energy Conservation -2

- Energy conservation measures may include:
  - manufacture, sale and use of fuel-efficient motor vehicles,
  - development and use of energy-efficient combustion and heat-recovery system in both industrial and domestic environments,
  - use of mass transit and/or car pooling,
  - construction and retrofitting of buildings to reduce energy loss,
  - manufacture of energy efficient appliances and equipment,
  - use of secondary (as compared to primary) materials in product manufacturing, recycling and reuse, etc.

II. Pollution Prevention *(P2)*

Summary:

1. Selecting process inputs that do not contain the pollutant or its precursors.
2. Operating the process to minimize generation of the pollutant.
3. Replacing the process with one that does not generate the pollutant.
4. Using less of the product whose manufacture generates the pollutant.

III. Installing Downstream Control Devices

- Takes a polluted stream, treats it to remove or destroy enough of the contaminants, so the stream is acceptable for discharge into ambient air.
- These are also known as “end-of-pipe” control devices.
- Many people think only of them when they think about air pollution control because they are widely applied and important.
- However, they appear third in this list of alternatives, because a prudent engineer will always first examine the previous two options to see if they are more practical and economical than a downstream control device.

III. Installing Downstream Control Devices

- The air pollution control engineer will receive more credit for
  - *devising a process change that prevents the formation of the pollutant*, than for
  - *designing an excellent device to control it* once it is formed.
- The three APC approaches need not be applied separately.

Example: A copper smelter used the following:

1. a tall stack for improved dispersion,
2. intermittent controls for dealing with difficult weather situations,
3. process changes to concentrate the off-gas, and
4. downstream controls to collect the sulfur oxides in the off-gas.

Sometimes, no one of the options, applied singly, would have been adequate to meet the applicable AP Standards.

Air Pollution Control Devices

Control of Gaseous Pollutants

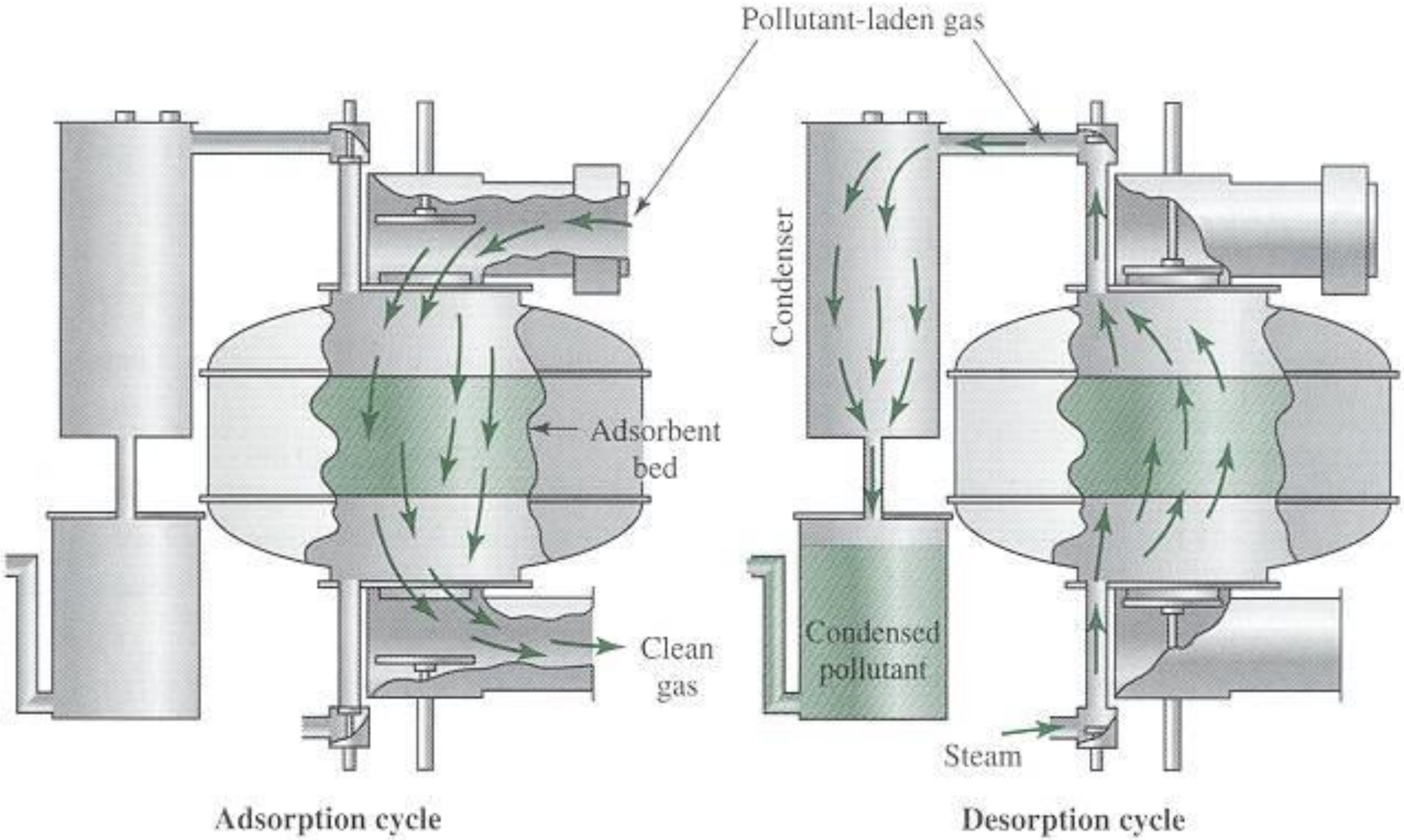
- Wet scrubbing (Gas absorption)
- Adsorption
- Incineration

Control of Particulates Pollutants

- Settling chambers
- Cyclones
- Baghouse filters
- Wet scrubbing
- Electrostatic precipitation (ESP)

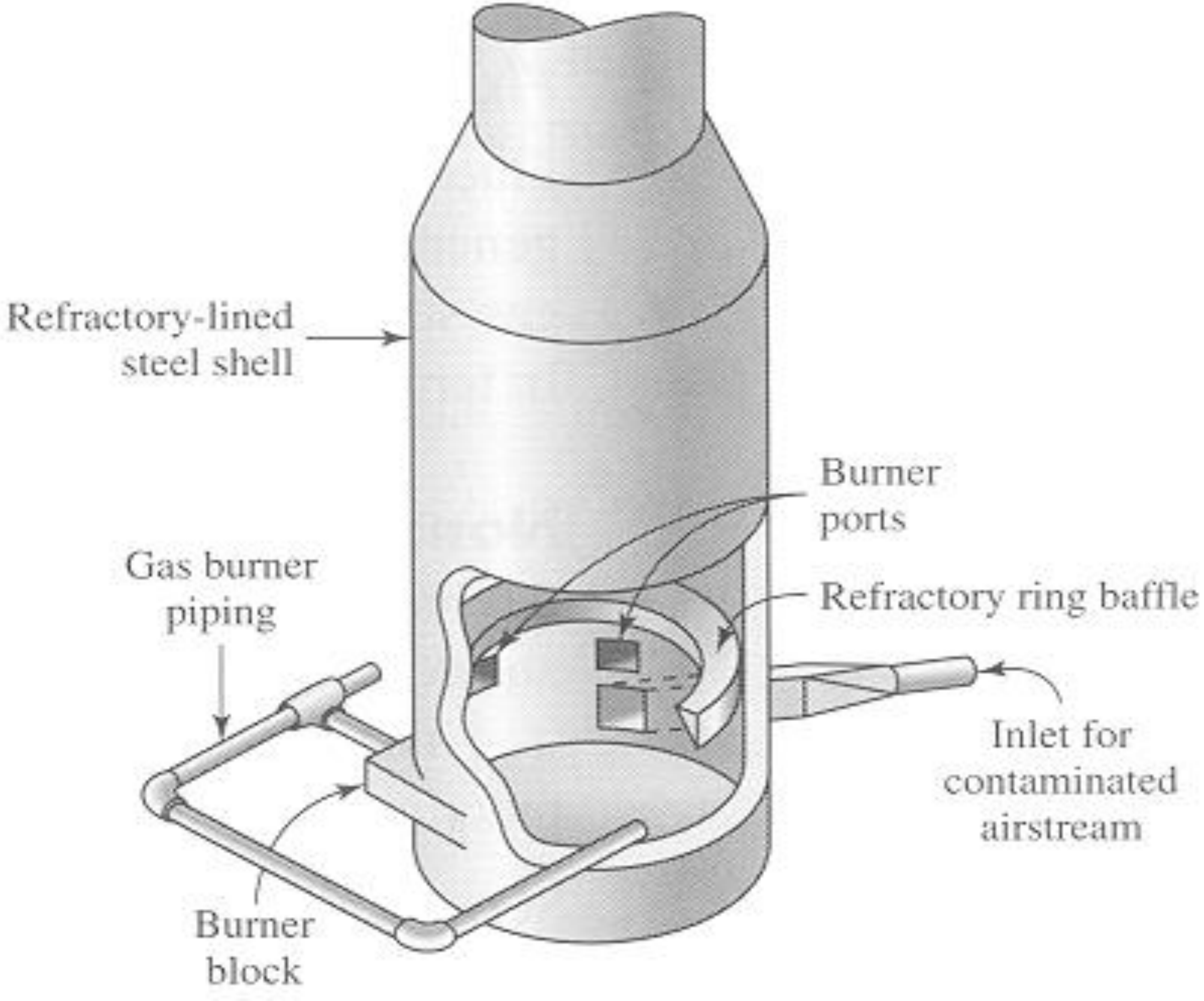
Wet Scrubber - Venturi

Adsorption

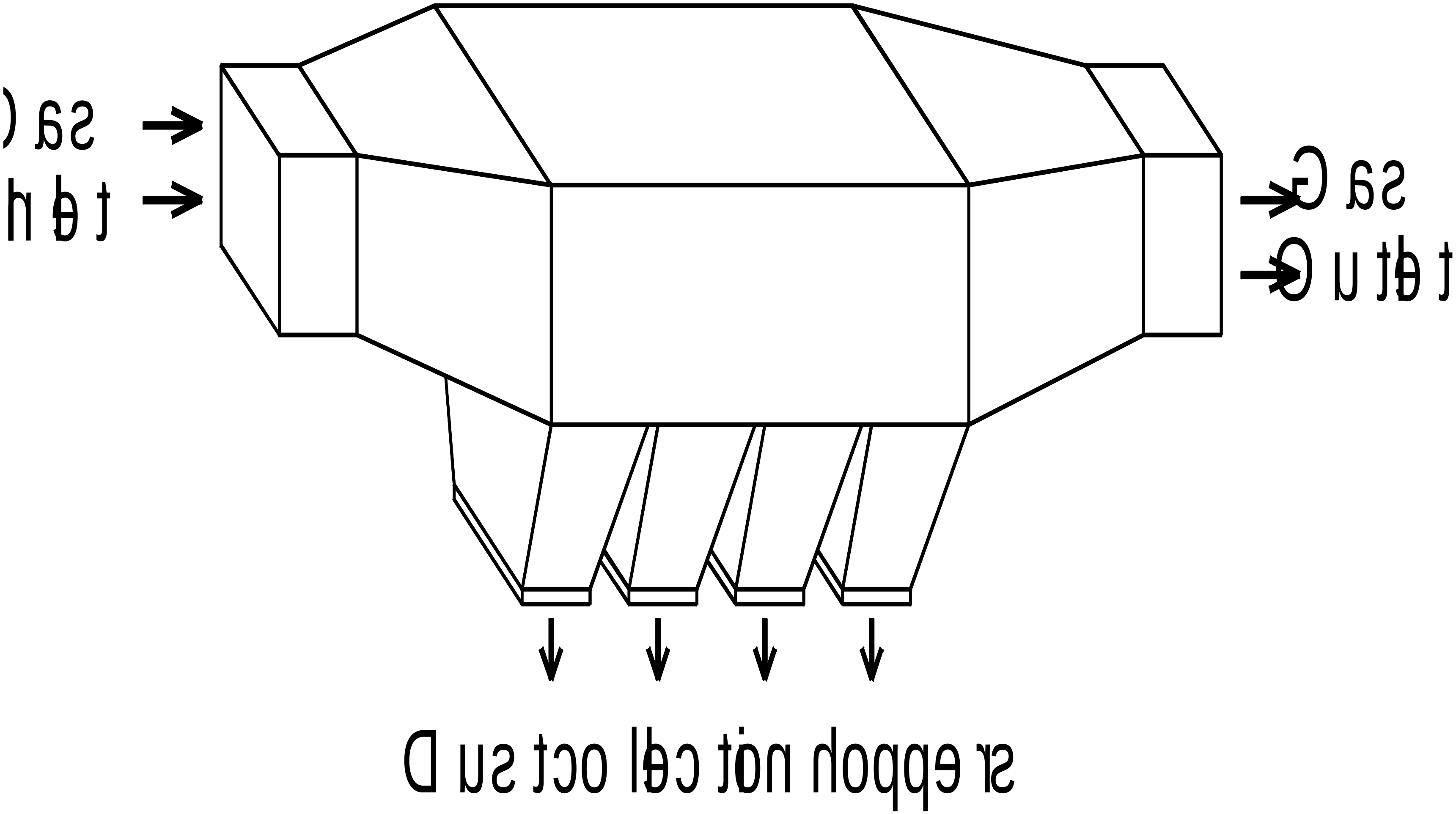


Pollutant-laden gas
Condenser
Adsorbent bed
Clean gas
Condensed pollutant
Steam
Adsorption cycle
Desorption cycle

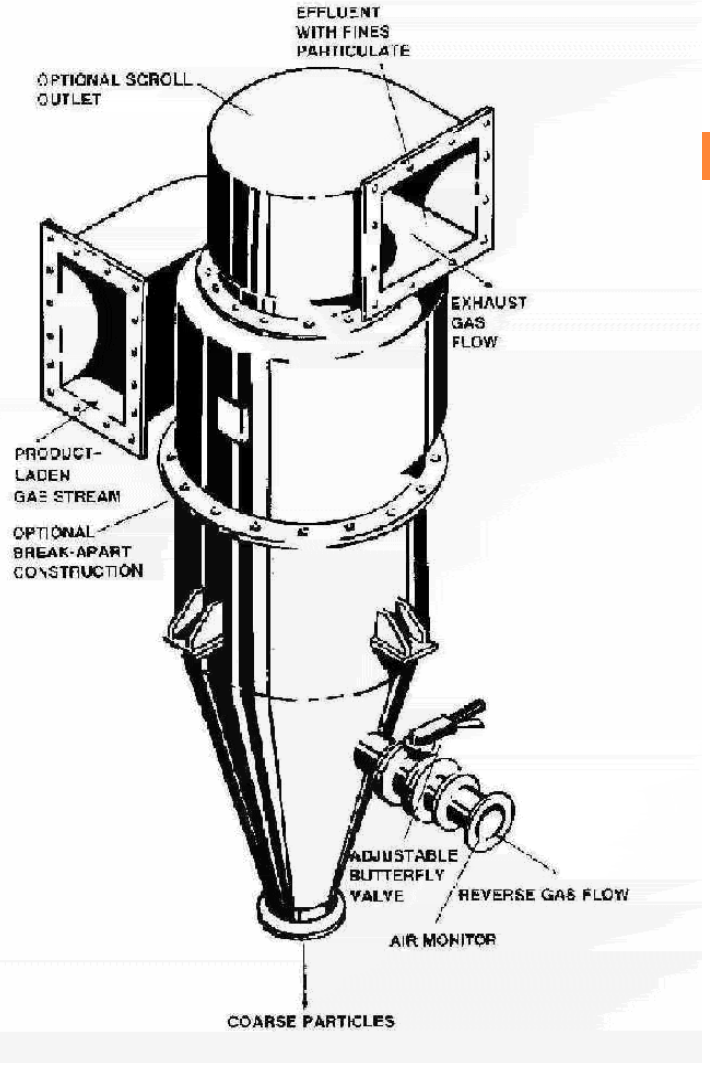
Incineration



Settling Chambers



Cyclones



EFFLUENT
WITH FINES
PARTICULATE
OPTIONAL SCROLL
OUTLET
EXHAUST
GAS
FLOW
PRODUCT-
LADEN
GAS STREAM
OPTIONAL
BREAK-APART
CONSTRUCTION
ADJUSTABLE
BUTTERFLY
VALVE
REVERSE GAS FLOW
AIR MONITOR
COARSE PARTICLES

Baghouse Filter

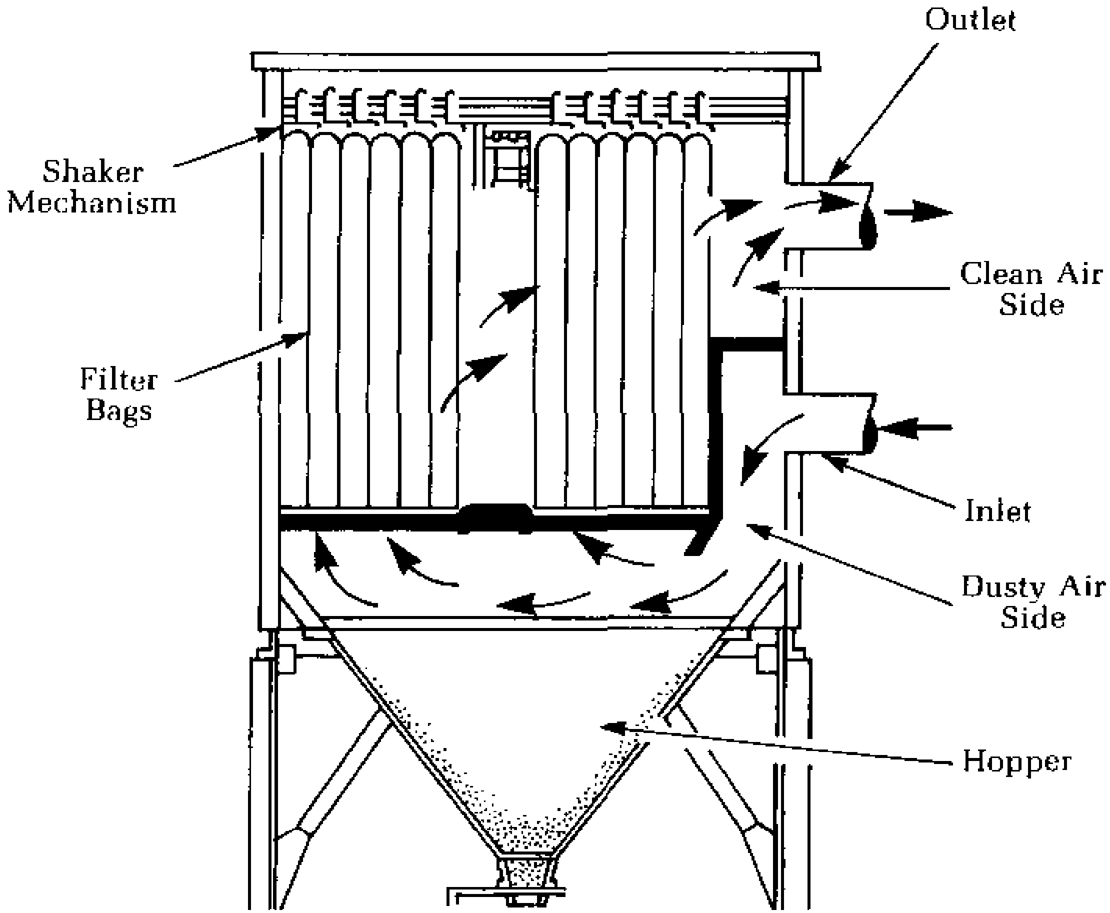
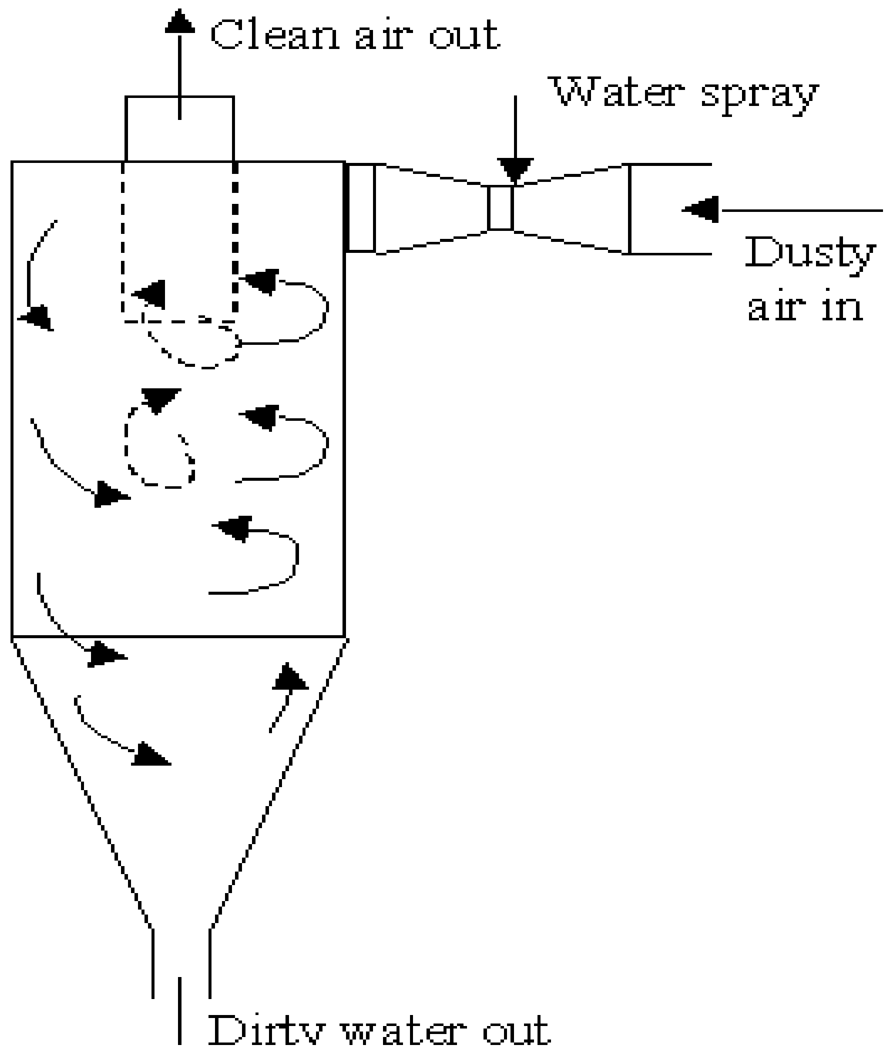
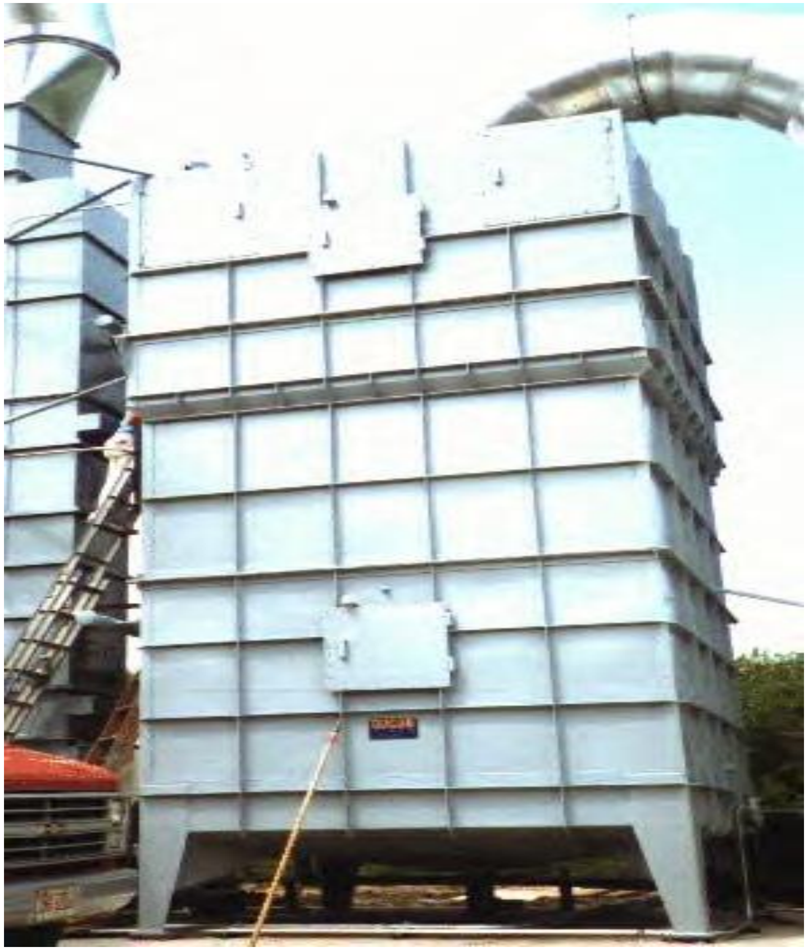


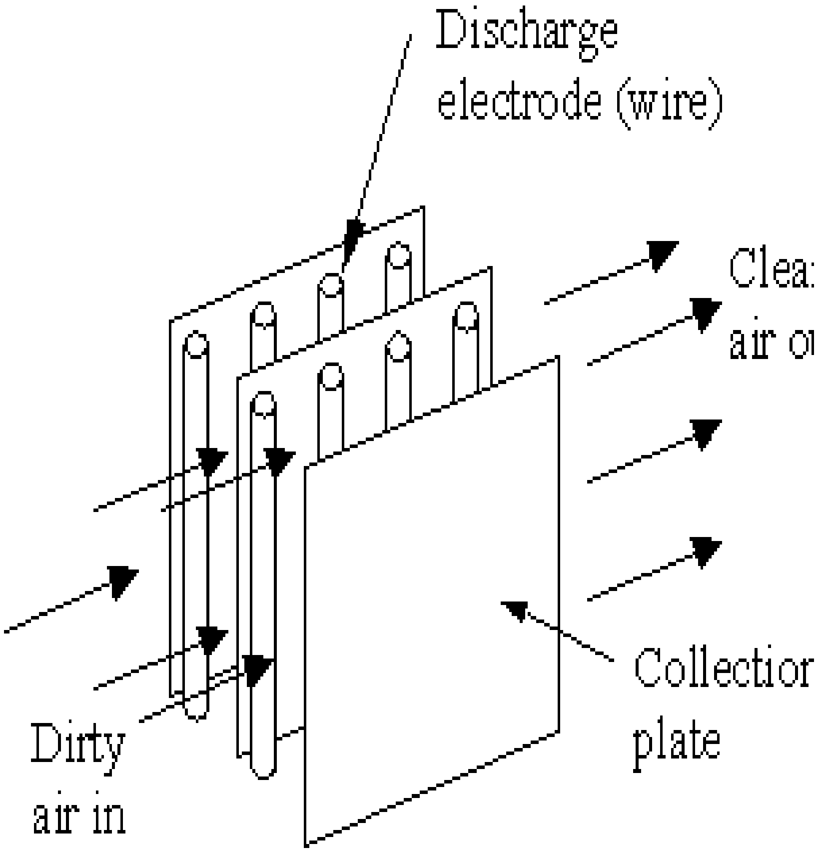
FIGURE 6-33
Baghouse.

Wet Scrubber



Electrostatic Precipitator (ESP)





1. Resource Recovery

- If the pollutant is a valuable material or a fuel, it may be more economical ***to collect and use*** it than to discard it.
- Generally, reclamation is only possible if the ***concentration is high*** enough in the waste stream.

  - This is frequently an incentive to modify the process to increase the concentration by decreasing the flow of waste gas.
  - A clear example of this is SO_2, which can be reacted with oxygen over a vanadium catalyst to produce sulfur trioxide (SO_3).
  - The latter, dissolved in water, forms sulfuric acid (H_2SO_4), a marketable product.

    - Its principal use is for the production of phosphate fertilizer; its price fluctuates with the demand for phosphate fertilizer.
    - It has many other uses, e.g., battery acid or as a permitted food additive.

1. Resource Recovery

- Those who have studied the economics of using this method to limit SO_2 emissions have generally concluded that it is economically prudent to do so (i.e., the sulfuric acid sales will pay for the sulfuric acid plant) if the concentration of SO_2 in the waste stream is 4 percent by volume or greater.

  - Hence smelters that extract metals from sulfide ores (copper, lead, zinc, molybdenum, nickel, and some others) ***can*** economically use this recovery process if they have a nearby market for the acid, but

  - coal-fired electric power plants ***cannot*** because the SO_2 content of their waste gases is normally about 0.1 percent.

1. Resource Recovery

Other examples of resource recovery in air pollution control are:

- The use of catalytic cracker regenerator off-gas and blast-furnace gas.
  - Both of these waste streams generally contain enough CO to make them valuable fuels.
  - Properly tuning engines, burners, and furnaces of all kinds reduces air pollutant emissions and also increases fuel efficiency.
  - Thus, such tuning is an air pollution control activity that also saves resources.
- Many organic solvents can be collected from waste streams and reused.
  - This step is only economical if the concentrations are large.
  - For this reason and for the reasons shown in the following sections, the air pollution control engineer should always examine ways to prevent the mixing of concentrated streams with dilute ones.

1. Resource Recovery

- Systems are designed to prevent the introduction of any more air than necessary into streams from which it may be possible to recover valuable products or that must be treated to minimize their effluent concentrations.
- A competent pollution engineer always looks for opportunities to convert waste streams to profitable products or valuable raw materials.
- Most of the obvious possibilities have already been exploited; less obvious ones are waiting to be discovered.

2. Ultimate Fate of Pollutants

- In designing any air pollution control system one should plan for the ultimate disposal of any wastes produced, because
  - the cost of that disposal can often be a significant fraction of the total cost of air pollution control.

- If the collected material is classified as hazardous waste then its disposal cost is many times that of an ordinary waste.

- Air pollution control processes that produce a solid waste, particularly one that may be classified as hazardous, are rarely chosen if there is any alternative process that produces no such solid waste.

2. Ultimate Fate of Pollutants

- First, we try to prevent the formation of pollutants (**pollution prevention**).
- If we cannot do that, we hope to capture them and put them to some good use (**resource recovery**).
- For most pollutants we cannot do that.
  - If the pollutants will burn, we often treat them chemically, e.g. by burning; this is true for most organic compounds **(Destruction).**
- Inorganic pollutants cannot be burned.
  - For these, most common ultimate fate is to be captured and placed in land **(Landfill disposal).**
  - That is the fate of most particulate pollutants (dust, ash, etc.).
- Most sulfur pollutants are ultimately converted to gypsum ($CaSO_4 . 2H_2O$), a non-hazardous solid and then are landfilled.

3. Design of A.P. Control Systems & Equipment

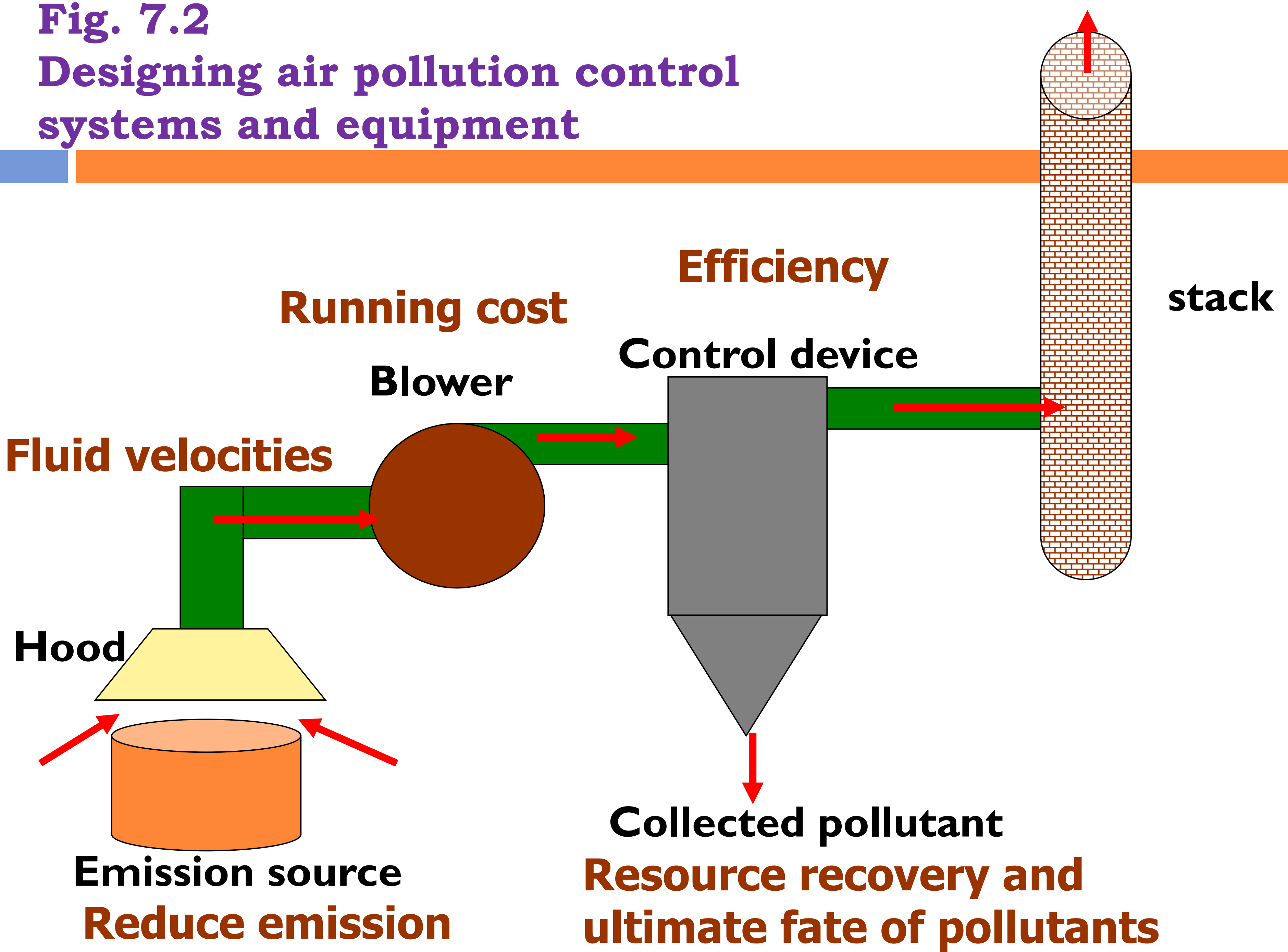
- Figure 7.2 shows a typical pollution control system consisting of some kind of contaminated gas capture device (a hood in this example); some kind of control device; some kind of gas mover, such as a fan or blower; some system for recycling or disposing of the collected material; and some kind of a stack.

  - It would be most unusual for one person to design all of these pieces of equipment.

  - Most likely for a small installation the fan and the control device would be selected from suppliers' catalogs.

  - Standard-size equipment is much cheaper and more reliable than custom- designed equipment.

Fig. 7.2
Designing air pollution control systems and equipment



3. Design of A.P. Control Systems & Equipment

- For large installations (e.g., a large electric power plant) the control device would be custom- designed, but made up by assembling the proper number of standard components in a custom-designed enclosure.

- The designer of the whole system would be expected to specify:
  1. the gas flow rate or velocity,
  2. the concentration and chemical nature of the pollutants in the gas,
  3. the required control efficiency, and
  4. the disposal method for the collected pollutant.

Fluid properties in APC equipment

- P &T: Most contaminated gas streams are either air or combustion gases:
  - at nearly atmospheric pressure, and
  - at a range of temperatures from room temperature to combustion temperatures.
- The ***"fluid mechanics"*** properties of combustion gases:
  - are close enough to those of air that approximate or preliminary fluid mechanical calculations are normally made as if combustion gases were air.
  - The same is not true for the chemical properties (Sec. 7.12 and Chapter 12).
  - Almost all industrial-sized flows of air or gases are turbulent.

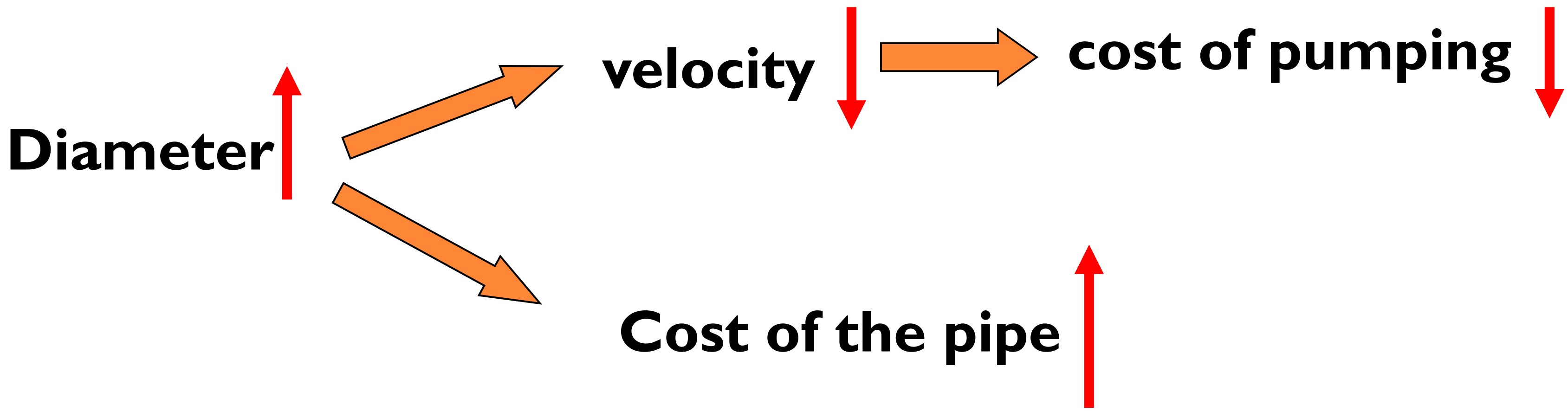
Fluid velocities in APC equipment

- The velocity in most air conditioning and other gas-flow ducts is about 40 to 60 ft/s (12 to 18 m/s), for economic reasons.
- As shown in any fluid mechanics book, there is an "economic velocity" for pumped fluid flows.
- This velocity minimizes the sum of pumping costs and the capital charges for the equipment.
- If we make the ducts or pipes bigger, the pumping cost is reduced, but the capital cost of the pipes or ducts increases.
- For ordinary steel construction and ordinary electric power costs, the optimal velocities are about 6 ft/s for water and 40 ft/s (12 m/s) for air.
  - Reynolds number for 12 m/s = 5.0E5; that is, 100 times the Reynolds number at the end of the transition region,
  - Thus we are quite safe in assuming that the flow of air and gases in ordinary ducts of any kind is *turbulent*.

Fluid velocities in APC equipment

Almost all industrial-sized flows of air or gases are turbulent .

40 to 60 ft/s (≈12 to 18 m/s)



Minimize sum of pumping cost and capital cost of pipes and ducts .

Fluid velocities in APC equipment

- Circumstances under which velocities are substantially different from 40 ft/s(12 m/s):

1. In some particulate control devices (Chapter 9) we use the inertia of the particle or of a droplet for collection purposes;
   - velocities up to 400 ft/s (120 m/s) are used.
2. In other particulate control devices we want the gas to remain as long as practical in the collecting device, in order to allow time for the control process to occur.
   - In electrostatic precipitators, the normal gas velocity is 3 - 5 ft/s (about 1-1.5 m/s).

Fluid velocities in APC equipment

3. If a gas stream is transporting a high specific gravity dust (e.g., heavy metal oxides), duct velocities up to 60 - 80 ft/s (18-23 m/s) are used, to prevent settling of the dust in the duct.

4. In countercurrent gas-liquid contacting devices, discussed in Chapters 9-11, the vertical upward gas velocity must be low enough that liquid drops can fall by gravity through the gas.
   - This limits the upward velocity to the settling velocity of the drops (Chapter 8), normally 10 to 20 ft/s (3 to 6 m/s).

Fluid velocities in APC equipment

5. Exception to the above statement that the flows in air pollution control are turbulent, flow-through the following units:.
   - Bag filters, granular adsorbents, catalysts.
     - In these flows the actual flow passages are the spaces between the individual particles making up the filter cake or the adsorbent or catalyst bed.
     - These are thousands of times smaller than the typical gas flow duct, so that the Reynolds number is very small.
     - In typical air pollution surface filters ("Baghouses") the superficial velocities are 1 to 3 ft/min (0.3 to 1 m/minute 0.016 to 0.05 ft/s) and the flow is normally *laminar.*

3. Minimizing Volumetric Flow Rate & Pressure Drop

- All waste gas streams must be propelled through the control device and the associated ductwork and exhaust stack.
  - Usually, a fan or a blower used for this.
  - The cost of operating these can be significant.

3. Minimizing Volumetric Flow Rate & Pressure Drop

$$Power = \frac{nRT_1}{\eta}\left(\frac{k}{k-1}\right)\left[\left(\frac{p_2}{p_1}\right)^{(k-1)/k} - 1\right]$$

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n = molar flow rate

R = universal gas constant

T_1 = inlet absolute temperature

k = heat capacity ratio = 1.4 for air and most waste gases

η = fan or blower efficiency

P_1 = inlet absolute pressure of the fan

P_2 = outlet absolute pressure of the fan

3. Minimizing Volumetric Flow Rate & Pressure Drop

$$P_2 = P_1 + \Delta P$$

$$when. \frac{\Delta P}{P_1} << 1$$

$$power \approx \frac{\dot{n} RT_1}{\eta}\left(\frac{k}{k-1}\right)\left[1+\left(\frac{\Delta P}{P_1}\right)\left(\frac{k-1}{k}\right)-1\right]$$

$$= \frac{\dot{n} RT_1 \Delta P}{P_1 \eta}$$

$$= \frac{Q\Delta P}{\eta}$$

Q ↓ ΔP ↓ → ***Power*** ↓

3. Minimizing Volumetric Flow Rate & Pressure Drop

$$(Actual\ flow\ rate) = (Std\ Flow\ Rate)\left(\frac{T}{T_{std}}\right)\left(\frac{P_{std}}{P}\right)$$

- In most of the air pollution control applications the pressure is close to atmospheric, so the right most term is close to one and is ignored.

$$(Actual\ flow\ rate) = (Std\ Flow\ Rate)\left(\frac{T}{T_{std}}\right)$$

- The size of the control devices and the power to pump the gas thru them are roughly proportional to the volumetric flow rate.

- Thus it will be economical to cool gases as much as possible before sending them to control devices, and it will be economical to locate the fan or blower at the place in the flow where the temperature is the lowest.

Efficiency, Penetration, Decontamination Factor

Let's say;

Q is flow rate

c is contaminant concentration

subscript 0 is for inlet, and *1* is for outlet

$$\text{Efficiency}, \eta = \frac{Q_0 c_0 - Q_1 c_1}{Q_0 c_0} = 1 - \frac{Q_1 c_1}{Q_0 c_0}$$

$$\text{Penetration}, p = 1 - efficiency = 1 - \frac{Q_1 c_1}{Q_0 c_0}$$

$$\text{Decontamination Factor, DF} = \frac{1}{penetration} = \frac{Q_1 c_1}{Q_0 c_0}$$

Obviously, if $Q_0 = Q_1$, the *Q*s cancel out of these three definitions

Efficiency, Penetration, Decontamination Factor

Example 7.4. We wish to use four collectors in series. Each of the collectors has an efficiency of 93 percent. What is the overall efficiency of the group of four in series?

We really want to know overall efficiency,

$$\eta_{\text{overall}} = 1 - \frac{Q_4 c_4}{Q_0 c_0}$$

We can write Eq. (7.7) four times and eliminate the intermediate values as shown here:

$$\eta_{\text{overall}} = 1 - \frac{Q_4 c_4}{Q_0 c_0}$$

$$\eta_1 = 1 - \frac{Q_1 c_1}{Q_0 c_0}$$

$$\eta_2 = 1 - \frac{Q_2 c_2}{Q_1 c_1}; \qquad Q_2 c_2 = Q_1 c_1 (1 - \eta_2) = Q_0 c_0 (1 - \eta_1)(1 - \eta_2)$$

$$\eta_3 = 1 - \frac{Q_3 c_3}{Q_2 c_2}; \qquad Q_3 c_3 = Q_2 c_2 (1 - \eta_3) = Q_0 c_0 (1 - \eta_1)(1 - \eta_2)(1 - \eta_3)$$

$$\eta_4 = 1 - \frac{Q_4 c_4}{Q_3 c_3}; \qquad Q_4 c_4 = Q_3 c_3 (1 - \eta_4) = Q_0 c_0 (1 - \eta_1)(1 - \eta_2)(1 - \eta_3)(1 - \eta_4)$$

$$\eta_{\text{overall}} = 1 - \frac{Q_4 c_4}{Q_0 c_0} = 1 - (1 - \eta_1)(1 - \eta_2)(1 - \eta_3)(1 - \eta_4)$$

Here the ηs are all equal, so that we can solve easily, finding

$$\eta_{\text{overall}} = 1 - (1 - 0.93)^4 = 0.999976$$

We can solve this same problem by asking what is the penetration of the series of collectors. Here we know that the penetration of each individual collector is $(1 - 0.93) = 0.07$. Then,

$$p_{\text{overall}} = \frac{Q_4 c_4}{Q_0 c_0} = \frac{Q_4 c_4}{Q_3 c_3} \cdot \frac{Q_3 c_3}{Q_2 c_2} \cdot \frac{Q_2 c_2}{Q_1 c_1} \cdot \frac{Q_1 c_1}{Q_0 c_0}$$

$$p_{\text{overall}} = p_1 \cdot p_2 \cdot p_3 \cdot p_4$$

In this case, all of the ps are equal, so

$$p_{\text{overall}} = p^4 = (0.07)^4 = 2.40 \times 10^{-5}$$

This example shows that when we have collectors in series, the penetration is generally more practical and simpler to use than the efficiency. ■

Efficiency, Penetration, Decontamination Factor

- Why the two definitions?
- The *efficiency* is:

"the ratio of what was done to the maximum that could be done".

  - It is simple and intuitive.
  - The *penetration* is the fraction *not* collected.
- Many calculations are easier and simpler in terms of the *penetration* than in terms of the *efficiency*.

Efficiency, Penetration, Decontamination Factor

- In the current air pollution literature it is becoming common to refer to the high efficiencies required for waste incinerators as ***"four nines***," i.e., a control efficiency of 99.99 percent.
- New regulations are being proposed that will require **"five nines," or "six nines"** for very toxic materials.
- If we have more than one control device in series, the mathematics of calculating their joint effect is much simpler if we use penetrations than if we use efficiencies.

Homogeneous / Non-homogeneous Pollutants

- Some pollutants, like SO_2 and CO, are homogeneous:
  - Every molecule of CO is identical to every other CO molecule.
- Other pollutants such as particles with various sizes and hydrocarbons are not homogeneous:
  - Fine particles are harder to capture, and more likely to cause health damage than coarse ones.
  - Benzene is harder to destroy in an incinerator than hexane and is probably a more serious health threat; both are hydrocarbons.
  - In both cases, the regulations apply to and the control devices operate on the mixture, not on individual particle sizes or hydrocarbons.
- Efficiency / Penetration:
  - cause no confusion when applied to homogeneous, but they are not always adequate when applied to heterogeneous pollutants.