LECTURE 11: AIR POLLUTION CONTROL

CE 433

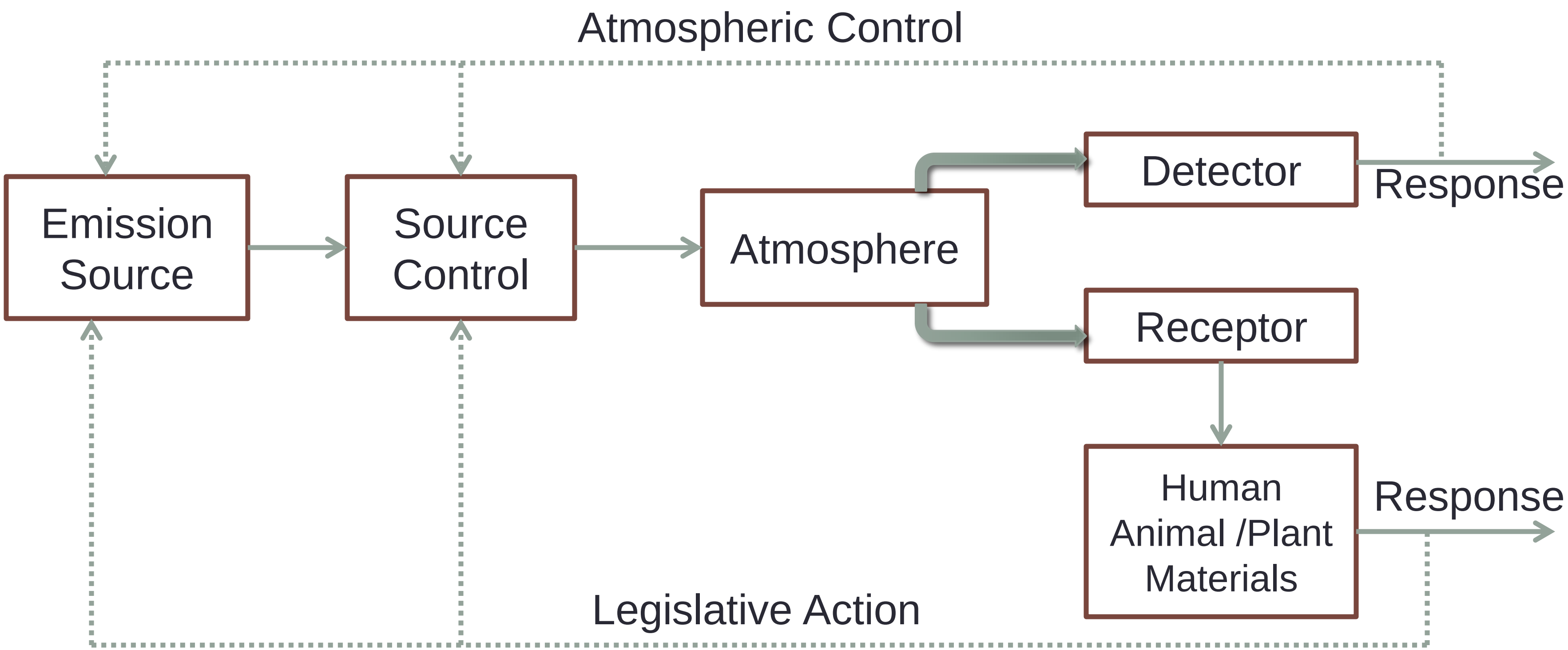
Excerpts from Lecture notes of Professor M. Ashraf Ali, BUET.

Natural Atmospheric Cleansing Processes

- The atmosphere has self-cleansing processes like rivers and streams. Major processes at work in the atmosphere are –
  - (1) **Dispersion:** By this process pollutants are mixed with air and their concentration is reduced in the atmosphere. (This is not really a removal mechanism)
  - (2**) Dry Deposition:** Settling and impaction of particulates/aerosols on surfaces

    Processes involved: - Gravitation settling, Flocculation & subsequent settling, adsorption
  - (3) **Wet Deposition:** Removal of pollutants/particulates by the action of rain, snow, fog, mist
- Close to the ground, “dry deposition” is the primary removal mechanism ; whereas at altitudes above 100 m, “wet deposition” is the predominant removal mechanism

Concept of Air Pollution Control



- Engineering Control
  - (1) Control at the source of emission
  - (2) Control for receptors (e.g. filtered air-conditions, gas mask)
  - (3) Control directed to atmosphere (e.g. diverting wind flow, discharging heat to alter temperature structure of atmosphere)

(2), (3) not shown in the figure above

Approaches to Contaminant Control: (Engineering Control)

- (1) Control for Receptors: Such as use of filtered air-conditions, gas masks.
- (2) Control directed to Atmosphere:
  - Discharging heat to alter temperature structure of atmosphere for achieving better dispersion/dilution of pollutants
  - Use of tall stacks to emit pollutants above inversion layer, so that ground-level pollutant concentrations are greatly reduced
    - However, pollutants released from tall stacks can travel long distances, so that effects of pollution can be felt at considerable distances away from the source
- (3) Control at the source of Emission
  - Substituting fossil fuel by less polluting energy sources (e.g. solar energy, hydro-power)
  - Proper use and maintenance of existing plant/machinery/equipment/car etc. (for example, an automobile with clean air filter, good crank case ventilation, correct idle-speed adjustment, proper carburetor setting, good spark plugs can reduce HC and CO emissions by 20 – 50%.
  - Most widely used methods of controlling emission at source is to install control equipment (designed according to principles of natural removal mechanisms).

Industrial Emission:

<u>Control Devices for Particulate Contaminants</u>

- Can be divided into five major groups:
  - Gravitational settling chambers
  - Centrifugal collectors
    - (a) Cyclones
    - (b) Dynamic precipitators
  - Wet Collectors
    - (a) spray towers
    - (b) wet cyclone scrubbers
    - (c) venturi scrubbers
  - Electrostatic precipitators
  - Fabric Filters

Gravitational Settling Chambers

- Provide enlarged areas to minimize horizontal velocities and allow particulates to settle out
- Usual velocity through settling chambers is between 0.5 to 2.5 m/s. For best results gas flow should be uniformly maintained at less than 0.3 m/s.
- Usually effective for particles > 50 μm.
- Some settling chambers are just enlarged conduits, while others have horizontal shelves and baffles (spaced about 2.5 cm apart), which shorten the settling path and thus improve removal efficiency
- Simple in design and operation, but require relatively large space for installation and have relatively low efficiency, especially for removal of smaller particles.

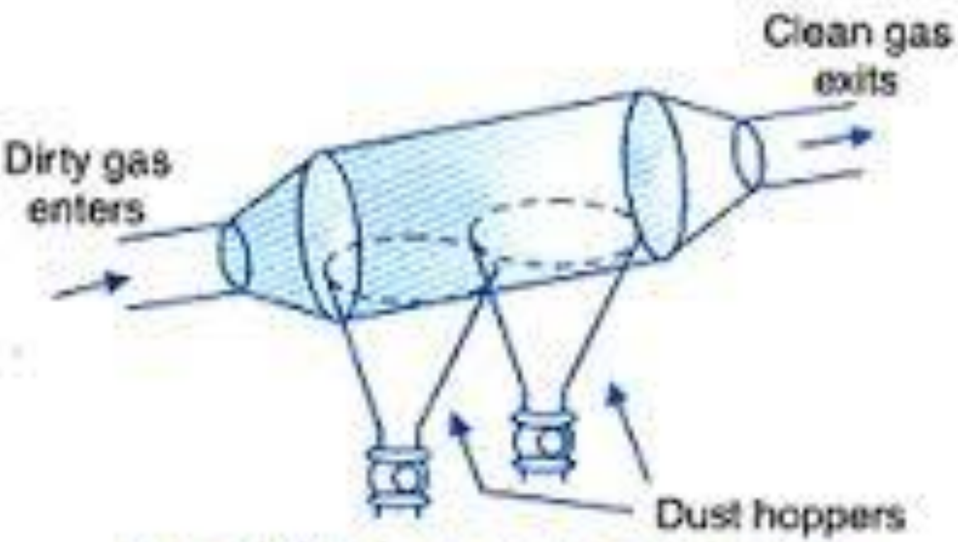


Fig. 5.3. Gravity settling chamber

Particle size

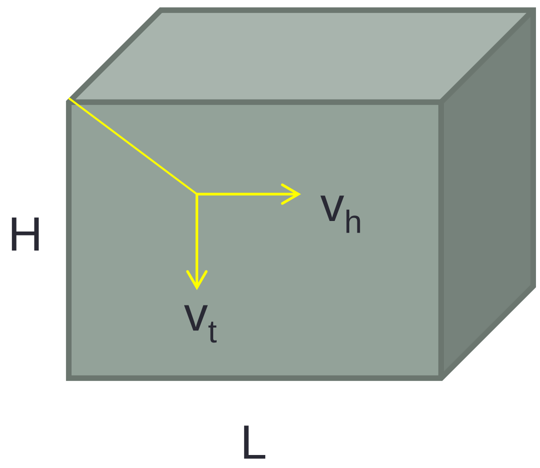
- Calculate minimum diameter of a particle that would be collected at 100% theoretical efficiency in a chamber of length L and height H
  - Terminal settling velocity of a particle can be described by Stoke’s law as follows:

$$v_S = \frac{g\,(\rho_P - \rho)\,D_P^2}{18\,\mu}$$

(μ: fluid viscosity; D_P: particle diameter)

Where, v_s = terminal settling velocity (m/s)
g = gravitational constant (m/s^2)
ρ_p = density of particle (kg/m^3)
ρ_a = density of air (~ 1.2 kg/m^3)
D_p = diameter of particle (m)
μ = viscosity of air ($N.S/m^2$; kg/m.s)

Particle size



- v_h = horizontal velocity (assumed to be same everywhere in the chamber)

(assume that if a particle settles to the bottom of the chamber it stays there, ie not re-entrained.)

$$dp_* = \left(\frac{18\mu v_h H}{g\rho_p L}\right)^{1/2}$$

- All particles larger than dp_* will be removed at 100% efficiency, while efficiency of smaller particles is the ratio of their settling velocities to the settling velocity of the dp_* particle
- Valid for quiescent conditions, which cannot be maintained in a flow through settling chamber. Hence a correction factor is often used.

- Fractional collection efficiency of particle of diameter d_p can be written as ($d_p < dp_*$)

$$\eta = \frac{L.g.dp^2\rho_p}{H.v_h.18\mu}$$

Problem 1

- Calculate the minimum size of particle that will be removed with 100% efficiency from a settling chamber under the following conditions:
  - Air: Horizontal velocity 0.3 m/s
  - Temperature 77degreeC
  - Particle: Sp Gr 2.0
  - Chamber: Length = 7.5 m
  - Height = 1.5 m

At 77degreeC of air, μ= 2.1 X 10^{-5-}kg/m.s

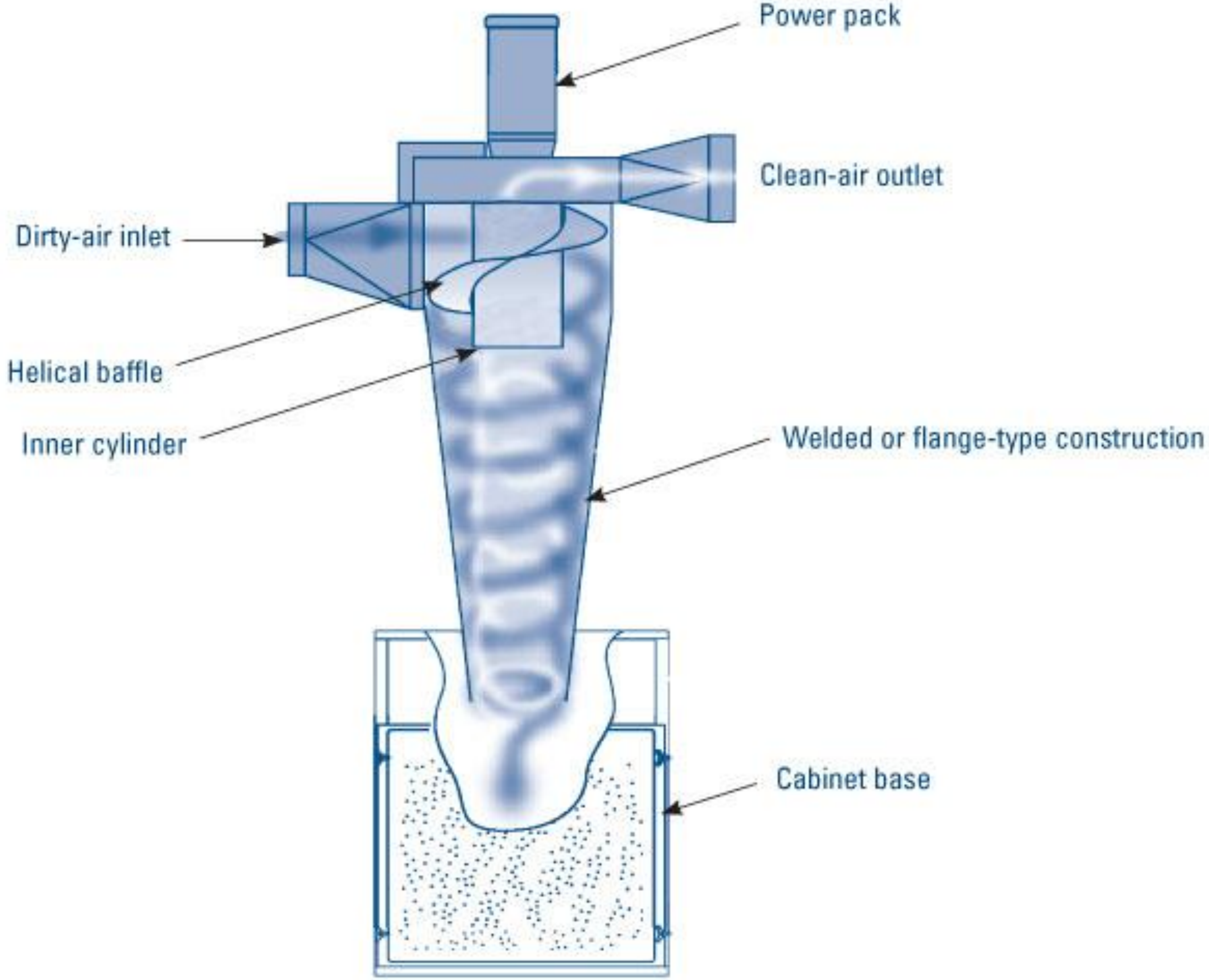
Problem 2

- Calculate the fractional efficiency of 20 μm particles in the above settling chamber

Centrifugal collectors

- Employ centrifugal force instead of gravity to separate particles from the gas stream
- Particles ranging from 5-20 μm can be removed
- Two general types of centrifugal collectors are used – cyclones and dynamic precipitators

Cyclone Collector

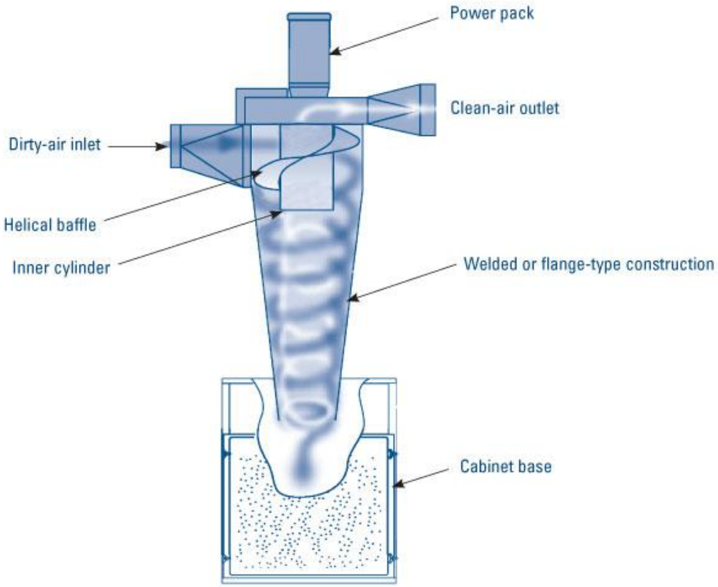


Cyclone Collector

Operating Principle:

- A cyclone collector usually consists of a cylindrical shell, conical base, dust hopper, and an inlet where the dust laden gas enters tangentially.
- Under the influence of centrifugal force generated by the spinning gas, the solid particles are thrown to the walls of the cyclone.
- The gas spiral upward at the inside of the cone
- The particles slide down the wall of the cone and into the hopper.
- The operating or separating efficiency of a efficiency of a cyclone depends on the magnitude of the centrifugal force; the greater the centrifugal force, the greater the efficiency

Control Devices for particulate Contaminant



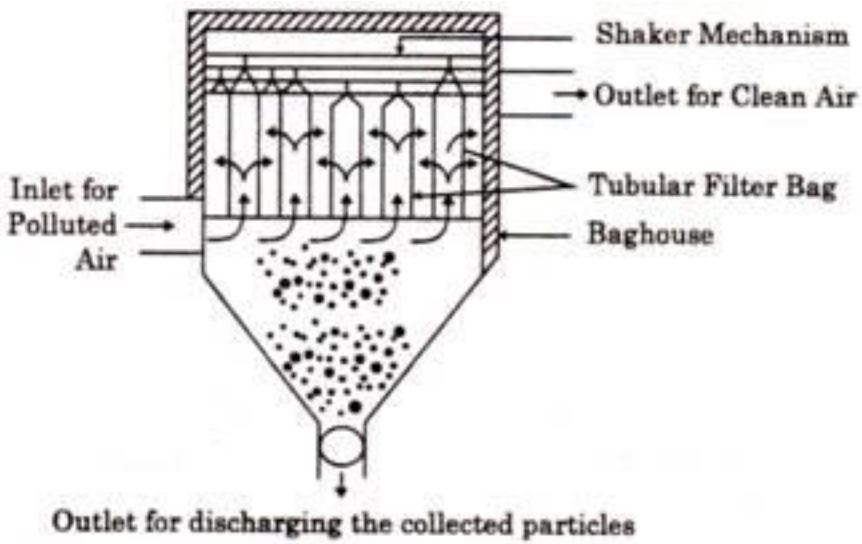


Fig. 5.3 Fabric Filter (Baghouse Filter)

Control Devices for Gaseous Pollutants

- (1) Adsorption: Passing a stream of effluent gas through a porous solid material (the adsorbent) contained in an adsorption pad.
  - Types of adsorbents: Activated carbon, alumina, silica gel etc.
- (2) Absorption: Involves bringing pollutant gas in contact with a liquid absorbent (solvent) so that one or more constituents of the pollutant gas are removed, treated or modified.
  - Types of absorbents: Aqueous solutions of alkalies (Na^+ and NH_3) and alkaline earth (Ca and Mg)

Control Devices for Gaseous Pollutants

- (3) Wet Collectors: Wet collectors, or scrubbers, remove particulate matter from gas streams by incorporating the particles into liquid droplets directly on contact.
- (4) Electrostatic Precipitators: Particulates moving through a region of high electrostatic potential tend to become charged and are then attracted to an oppositely charged area where they can be collected
- (5) Fabric Filters: The particulate laden gas stream passes through a woven fabric that filters out the particulate matter and allows the gas to pass through

Control Devices for Gaseous Pollutants

- (5) Fabric Filters: Operating principle:
  - Particle-laden gas stream passes through a woven or felted fabric that filters out the particulate matter and allows the gas to pass through
  - Small particles are initially retained on the fabric by direct interception, inertial impaction, diffusion, electrostatic attraction, and gravitational settling
  - After a dust mat has formed on the fabric, more efficient collection of submicron particles is accomplished
  - Filter bags, usually tubular or envelope-shaped, are capable of removing most particles as small as 0.5 μm and will remove substantial quantities of particles as small as 0.5 μm
  - Filter bags ranging from 1.8 to 9 m long, can be utilized in a bag house filter arrangement. The upper ends are closed and the lower ends are attached to an inlet manifold.
  - The design of fabric filters is based on filtering rates, or air to cloth ratios. Filtering rates range from: 0.5 to 5 m/min (m^3 air/min.m^2 cloth)

Emission from Vehicle: Combustion Emission

- <u>Internal Combustion engines:</u>

The most common form is a 4-stroke, spark ignited, piston engine.

The single most important factor in determining emissions from an internal combustion engine is the ratio of air to fuel ratio.

Average composition of fuel: C_7H_{13}

For complete combustion, 1 mole of fuel requires 10.25 moles of O_2.

Molar ratio of "O" and "N" in air = 3.76

We can write :

$C_7H_{13} + 10.25\ O_2 + 38.5\ N_2 \rightarrow 7CO_2 + 6.5\ H_2O + 38.5\ N_2$

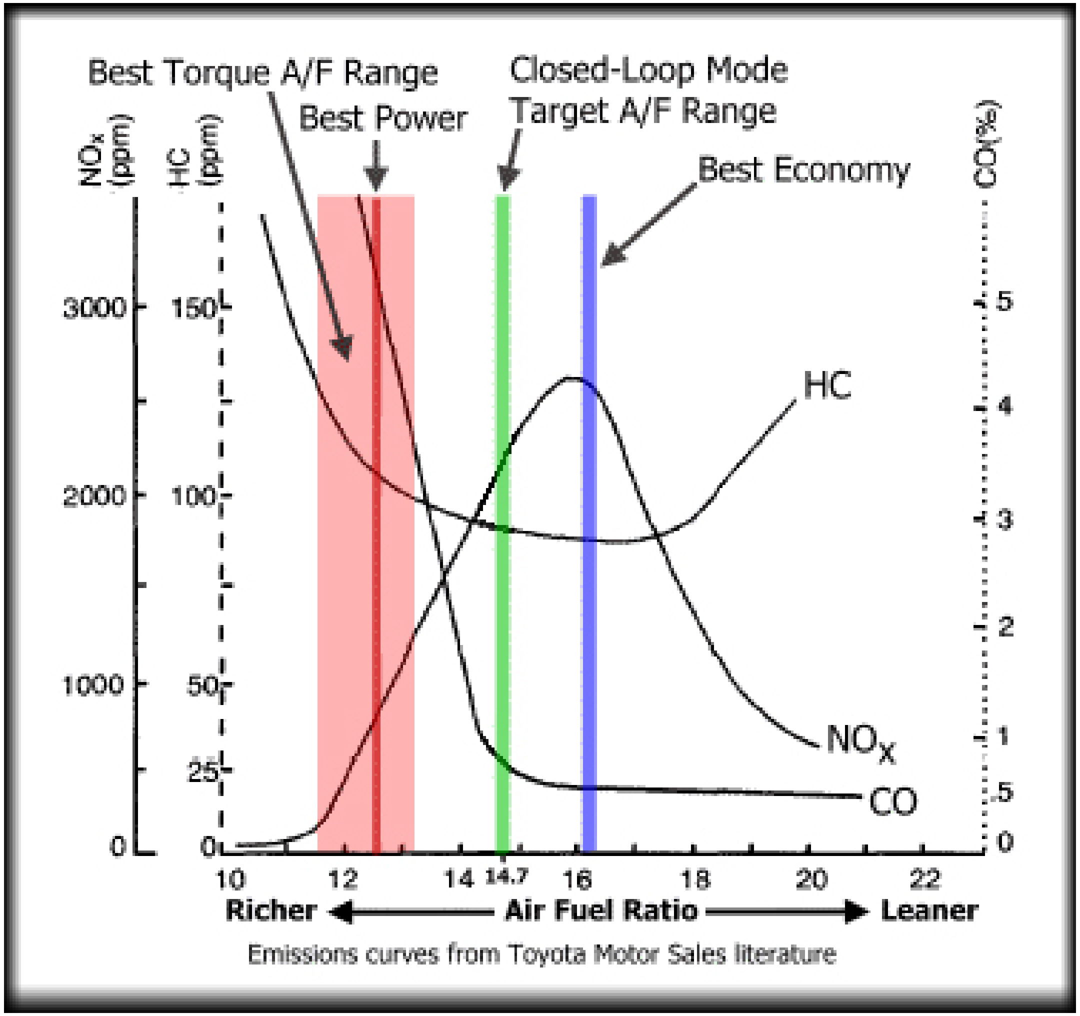
Considering air to be made up of only O_2 and N_2, the air fuel ratio needed for complete oxidation of gasoline:

Air/Fuel = $(10.25\ O_2 + 38.54\ N_2)/C_7H_{13} = 14.5$

This ratio (14.5) is known as the stoichiometric ratio for gasoline.

- If Actual air-fuel mixture has less air than what the stoichiometric ratio indicates, the mixture is said to be "rich".
- If more air is provided than necessary, the mixture is said to be "lean".

Figure: Effect of air-fuel ratio on emissions, power, and fuel economy



Effect of air-fuel ratio on pollution

- A “rich” mixture encourages production of CO and unburned hydrocarbons, since there is not enough oxygen for complete combustion
- On the other hand, a lean mixture helps reduce CO and HC emissions (unless the mixture becomes so lean that misfiring occurs)
- For rich mixtures, the lack of oxygen lowers the combustion temperature, reducing NO_x emissions. In the other direction, beyond a certain point, lean mixtures may have enough excess air that the dilution lowers flame temperature and reduces NO_x production. (figure)
- Also, maximum power is obtained for a slightly “rich” mixture, while maximum fuel economy occurs with slightly lean mixtures.
- Other factors influencing pollution include: ignition timing, compression ratio, combustion chamber geometry, and whether the vehicle is idling, accelerating cruising or decelerating.

Vehicular Pollution Control

- Using Alternative Fuels
  - Compressed Natural Gas (CNG)
  - Liquefied Petroleum Gas (LPG)
- Using Alternative Vehicle Technology
  - Fuel Cell Vehicles
  - Electric Vehicles
  - Hydrogen Fueled Vehicles
  - Hybrid Vehicles
- Pollution Control From IC Engines
  - Engine Replacement
  - Regular Engine Maintenance (lubricating oil, filters, spark plugs, coolant, etc.)
  - Retrofit options/post-engine Devices
    - Thermal Reactor
    - EGR (Exhaust Gas Recirculation)
    - Catalytic Converter (CC)
      Diesel particulate Filter (DPF)
    - Diesel Oxidation Catalyst (DOC

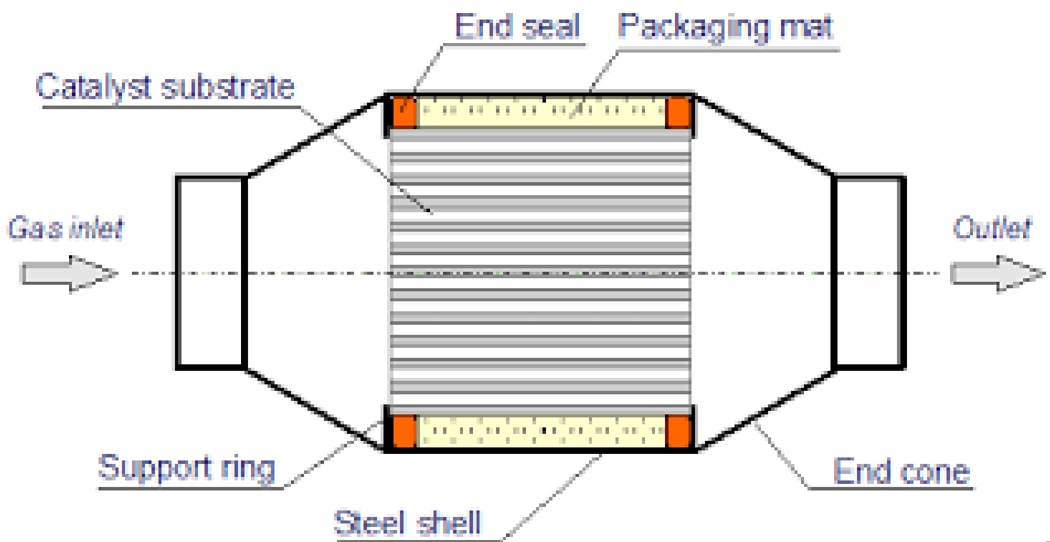
Thermal Reactor

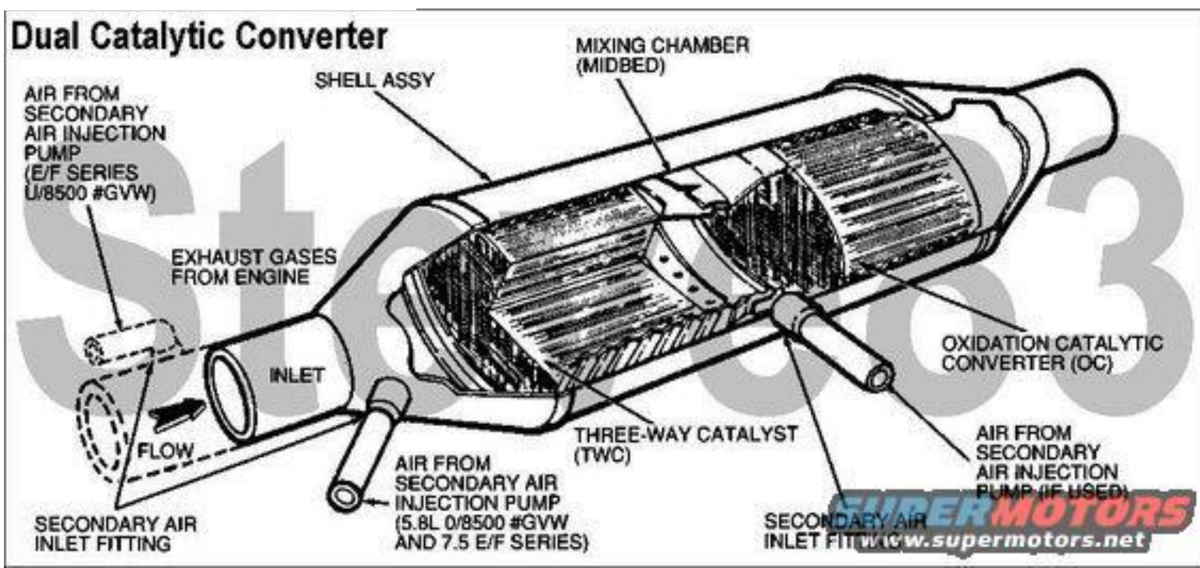
- A thermal reactor is basically an afterburner that encourages the continued oxidation of CO and HC after these gases have left the combustion chamber
- Exhaust gases in the reactor are kept hot enough and enough oxygen is provided to allow combustion to continue outside the engine itself, thus reducing CO and HC emissions
- Usually, the system is designed to cause the engine to run “rich” in order to provide sufficient unburned fuel in the reactor to allow combustion to take place. This has secondary effect of modestly reducing NO_x emissions, although it also increases fuel consumption since some fuel is not burned in the cylinders

Exhaust Gas Recirculation (EGR)

- Some degree of control of NO_x can be achieved by recirculating a portion of the exhaust gas back into the incoming air-fuel mixture.
- This relatively inert gas that is added to the incoming mixture absorbs some of the heat generated during combustion without affecting the air-fuel ratio. The heat absorbed by the recirculating exhaust gas helps reduce the combustion temperature and hence, helps decrease the production of NO_x.
- The coupling of exhaust gas recirculation (EGR) with a thermal reactor, reduces emissions of all three pollutants, CO, HC and NO_x but at the expense of performance and fuel economy.

Catalytic Converter (CC)





Catalytic Converter

- Catalytic Converters are connected to a car's exhaust system
- Catalysts (Noble Metals): Platinum (Pt), Rhodium (Rd), Palladium (Pd) (About 4-5 g/convt)
- 2-way (oxidation) catalytic converter: oxidizes HC and CO to CO_2
  - Catalysis: Pt, Pd
  - Oxidation Reactions: $CO + O_2 \rightarrow CO_2$; $HC + O_2 \rightarrow CO_2 + H_2O$
- 3-way (Redox) Catalytic Converter: also reduces NO_x to N_2
  - Catalysts: Pt, Rd, Pd
  - Oxidation Reactions: $CO + O_2 \rightarrow CO_2$; $HC + O_2 \rightarrow CO_2 + H_2O$
  - Reduction Reaction: $NO_x \rightarrow N_2 + O_2$

Catalytic Converter

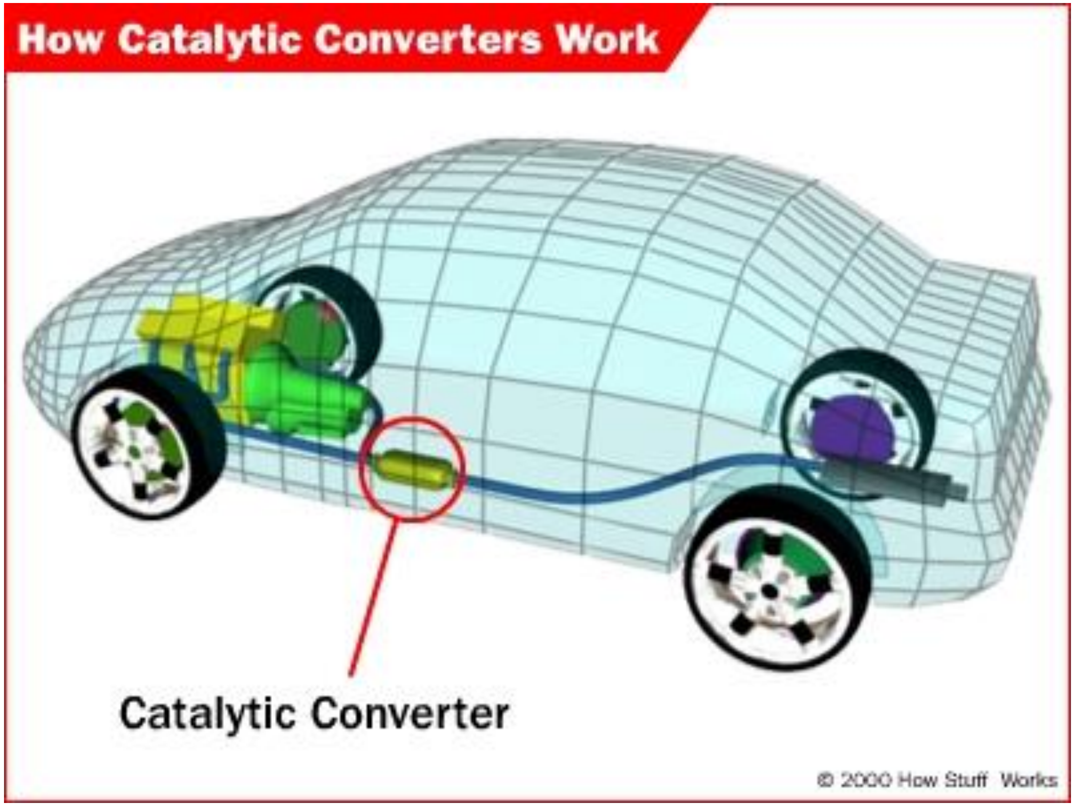
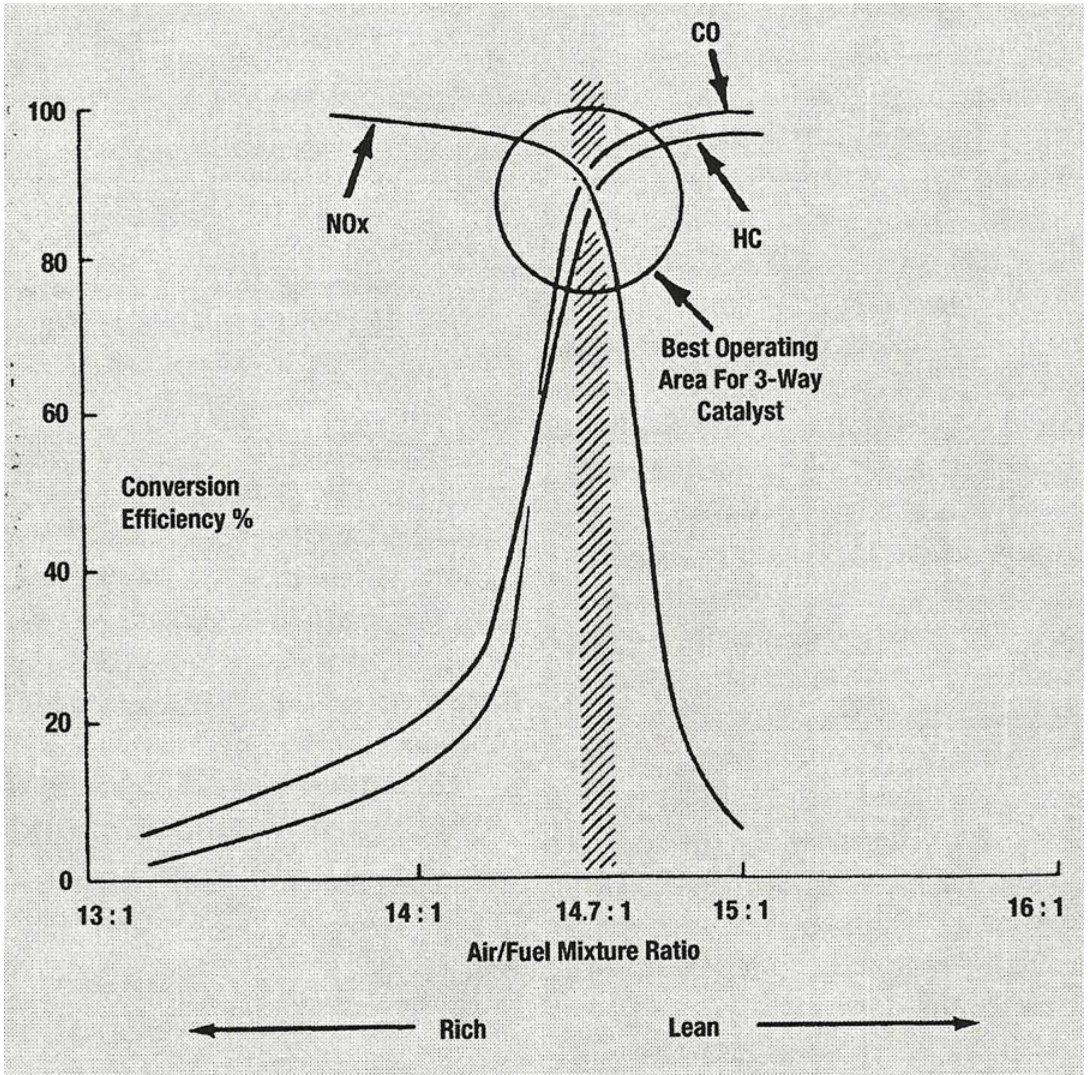


Figure: Effect of Air-fuel ratio on conversion efficiency in a catalytic converter



Catalytic Converter: Not a Magic Box

- Catalytic converters start working effectively as they get warm above 250 – 300 °C. The reactions taking place are exothermic. Converter material should be able to withstand up to 1000°C. Generally heat shields are used to protect other parts of vehicle body.
- Extra oxygen is needed to support the reactions, that might be provided by lean air-fuel ratio or pump-type air injection.
- Unleaded (Pb-free) fuel is essential to prevent "fouling" of catalytic converters.
- Catalytic converters must operate within a very narrow band of air-fuel ratio:

Catalytic Converter: Not a Magic Box

- Catalytic converters must operate within a very narrow band of air-fuel ratio:
  - If air-fuel ratio > 14.9, conversion of NO_x-N_2 is reduced significantly
  - If air-fuel ratio<14.8, conversion of HC and CO to CO_2 is reduced significantly

  This requires precise electronic control systems that monitor and control air-fuel mixture in an engine.
- Most common cause of failure of CC is an engine that pumps too much unburned fuel, which can overheat or carbon-clog the catalyst.
- Fuel specification like sulfur content should be maintained to prevent catalyst poisoning, deteriorating performance
- Fouling, clogging, meltdown, breakage of ceramic substrate may cause a converter to be ineffective , and/or plug it and raise back pressure.

Diesel Engines

- In diesel engines, fuel is injected directly into the cylinder, and there is no conventional ignition system with plugs, points and condenser since the fuel ignites spontaneously during compression stroke.
- Since they do not depend on spark ignition, they can run on very lean mixtures. Thus they are inherently more fuel efficient.
- Since diesel run with very lean mixtures, emissions of HC and CO are inherently low.
- However, because high compression ratios create high temperatures, NO_x emissions are relatively high.
- In addition, diesels emit significant quantities of carbonaceous particles known as “soot”, some of which are mutagenic and possibly carcinogenic.
- Controlling NO_x with catalytic converters is difficult. Since fuel is burnt with so much excess oxygen, catalysts that require a lack of oxygen to reduce NO_x are ineffective.