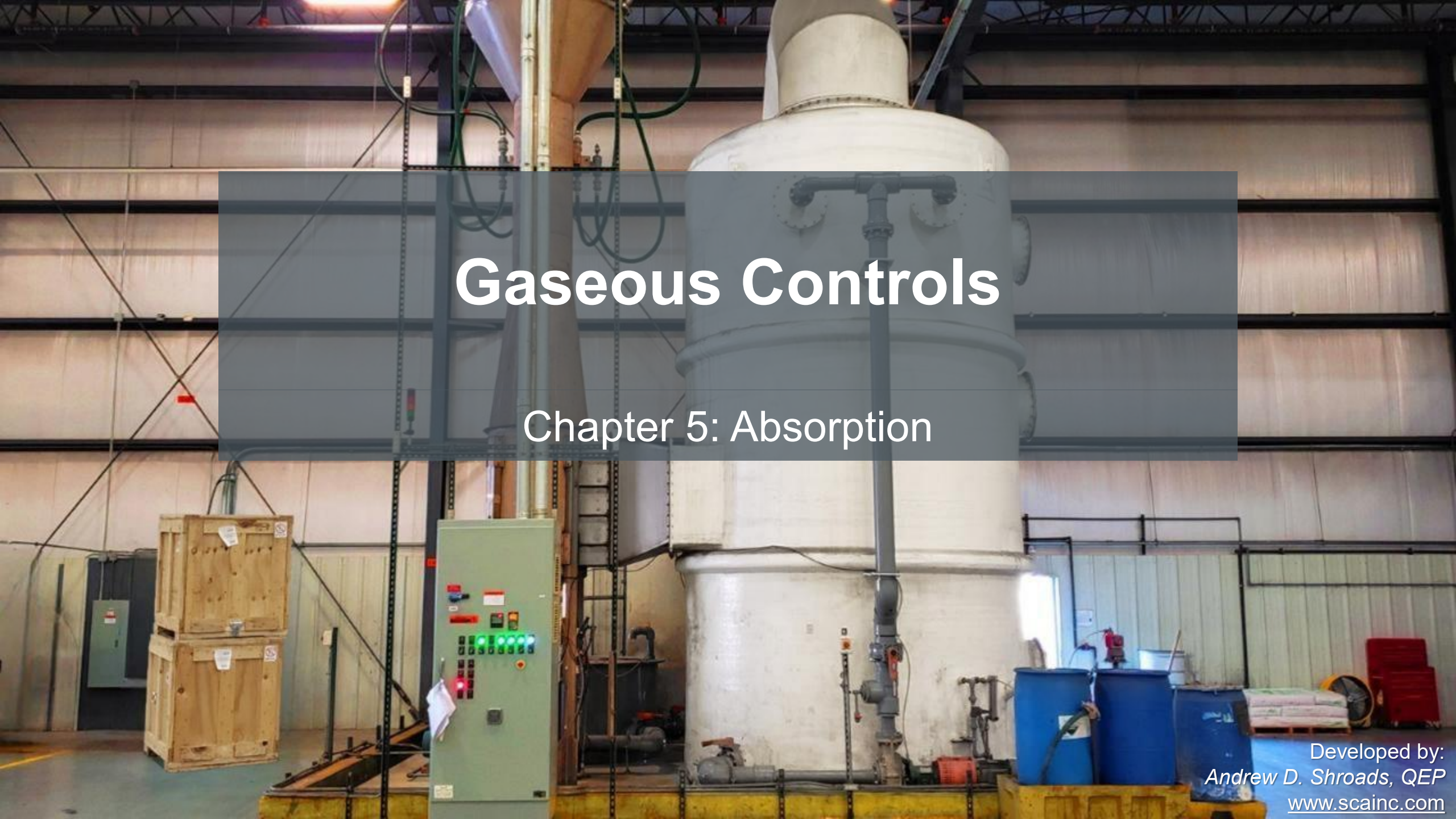


Gaseous Controls

Chapter 5: Absorption

Developed by:
Andrew D. Shroads, QEP
www.scainc.com

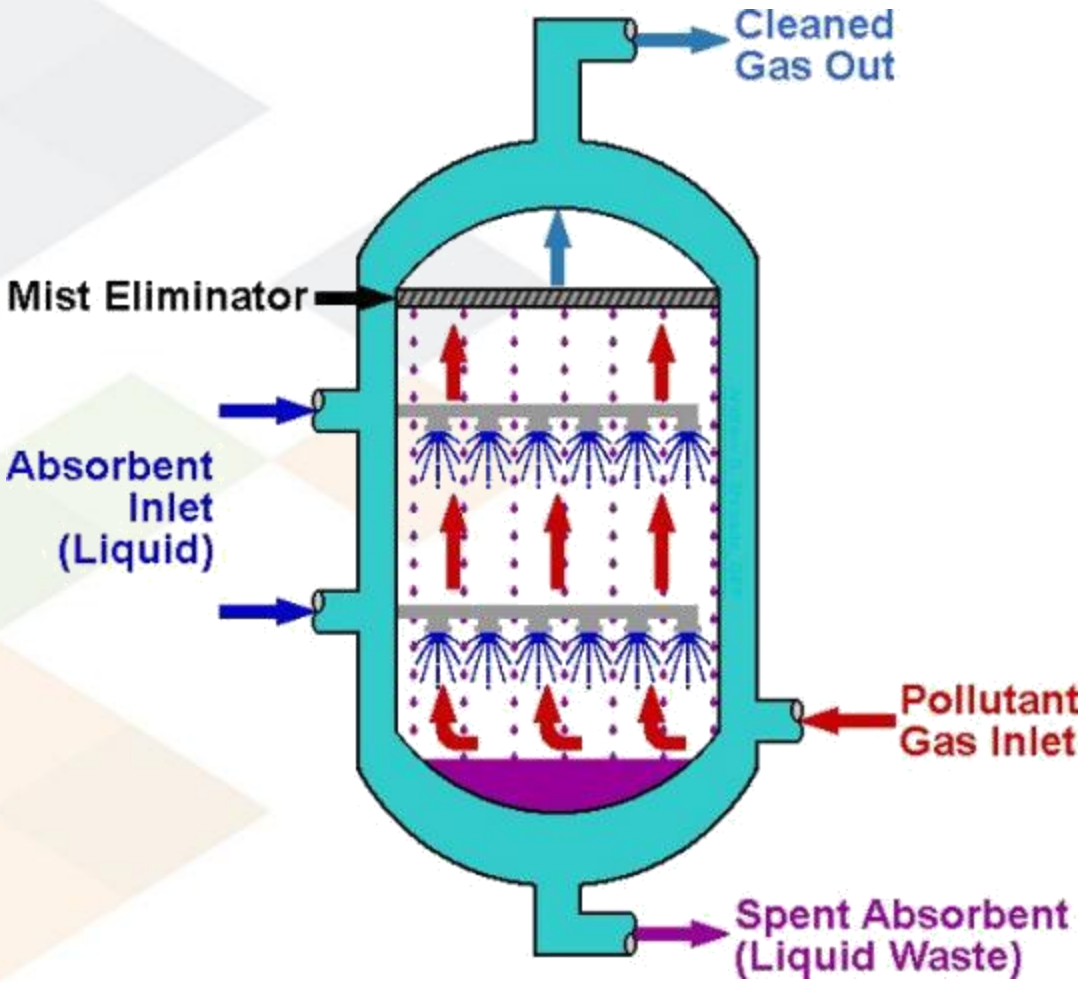
Chapter 5: Absorption
Objective

To improve understanding of absorption control technologies

- What are the types of absorption controls?
- How do absorption controls operate?
- How are absorption controls designed?
- What is the expected control efficiency for absorption?
- What are common problems with absorption control?
- How are absorption controls monitored?

Absorption

- Gaseous pollutants in exhaust captured by solvent
  - Wet scrubber for gaseous pollutants
  - Transfers air pollutants to solvent (scrubber liquor / liquid)
  - Mist eliminator reduces droplets exhausting from stack
- Must dispose of, regenerate, or treat spent solvent

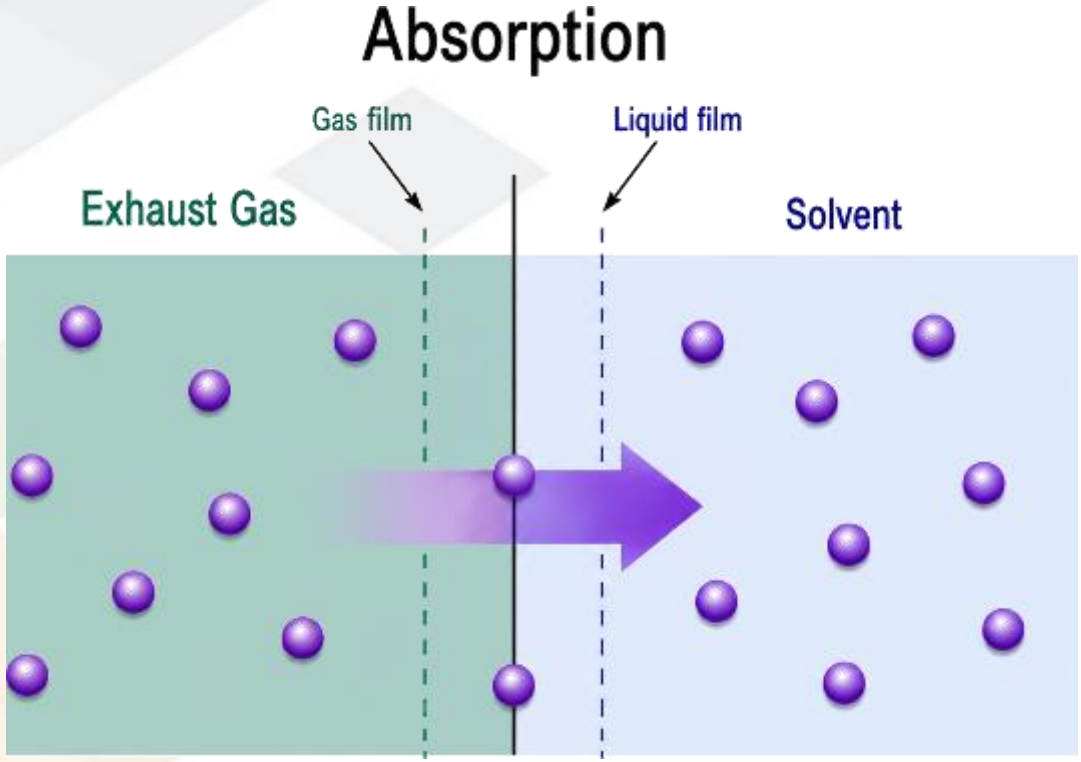


Absorption Equilibrium

- Net equilibrium state of mass transfer from gas to liquid
  - No more absorption can occur (equal numbers of molecules transferring in and out of liquid)
  - Equilibrium conditions change by pollutant, temperature, and concentration
- Two options to address equilibrium:
  1. Provide additional scrubbing liquid (continuous)
  2. Chemically react pollutants so they do no return to gas phase

Two Film Theory

- At gas-liquid interface, there are two films: gas and liquid
  - Mass transfer happens between these films
- Henry's Law governs mass transfer
  - At a constant temperature, gas solubility is proportional to partial gas pressure
  - Henry's Law constants describe solubility of gas



Absorption (Wet Scrubber)

Pollutants in exhaust (absorbates) are removed by being absorbed into a solvent via physical or chemical reaction

1. **Physical**: Absorbate (pollutant) held in solvent (absorbent); reversible (desorption); no new chemicals formed
   - Physical mass transfer, typically reversed (regenerated) onsite
2. **Chemical**: Absorbate (pollutant) is converted in a chemical reaction with solvent (absorbent)
   - New chemicals created are usually water and salts
   - Spent solvent must be disposed of or treated prior to discharge

Chapter 5: Absorption
Video

VOC 3.0 - Absorption Intro.mp4

PM 3.0 - Wet Scrubbers Intro.mp4

Chapter 5: Absorption Controls



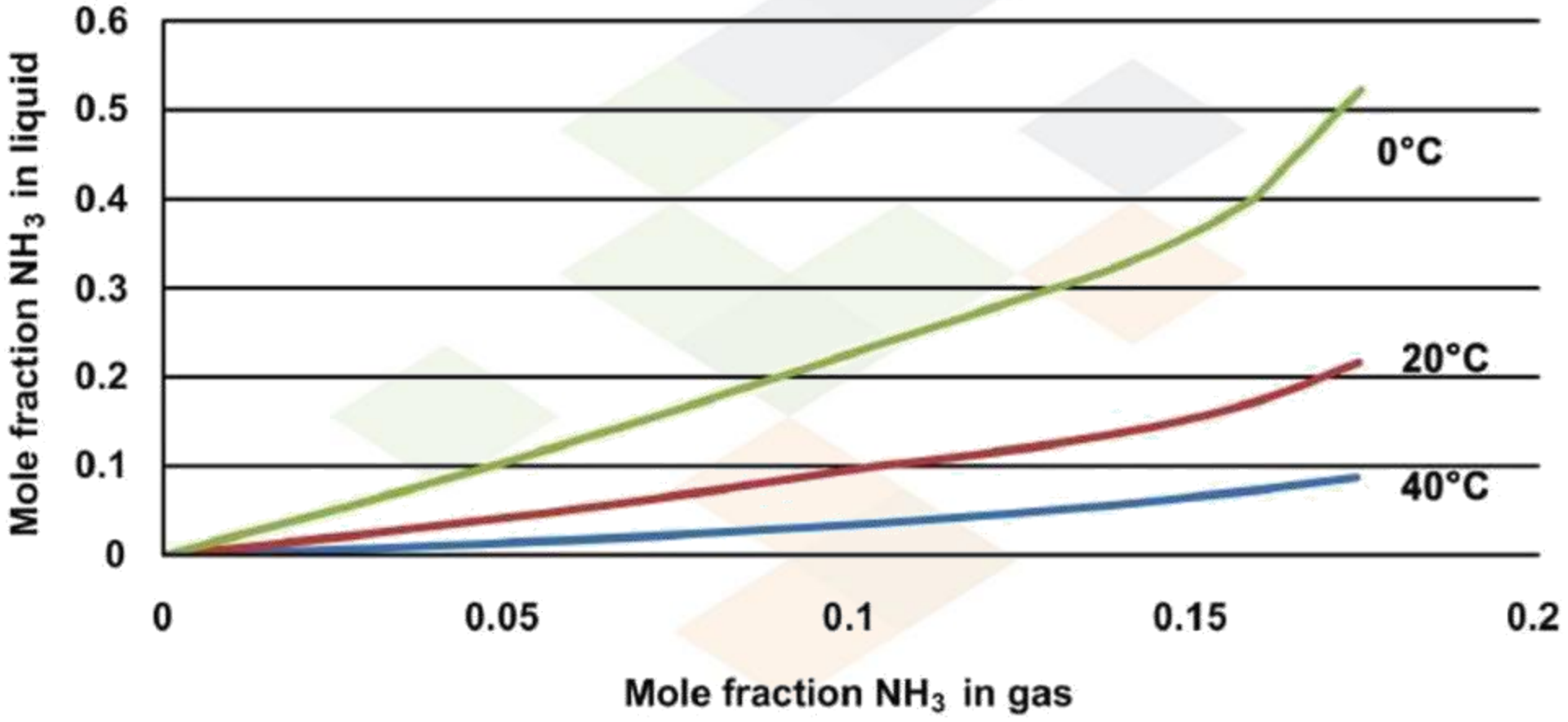
Exhaust Gas

- Gas velocity cannot exceed ability for liquid to drain by gravity (tower scrubbers) or liquids will collect (flood)
  - Operating gas flow rate usually 60-75% of rate that would cause flooding
- Slow & Turbulent: Better control if gases and liquid have more time and are agitated (mixed)
  - Greater time for diffusion allowing gases to migrate into liquid droplets or films
  - Scrubber systems are designed for gas flow, rather than amount of solvent
- Pre-coolers required to reduce high exhaust gas temperatures (if >212ºF, water may boil and reduce collection efficiency)

Solubility

- Solubility of gaseous pollutants in solvent varies by gas concentration and temperature
  - Gas solubility increases as temperature decreases
- Higher control efficiencies for higher pollutant concentrations
  - For lower concentrations, increase gas-liquid contact to maximize control efficiency
- Change(s) in facility process after installation of control equipment may reduce control efficiency by affecting solubility
- Absorption offers multi-pollutant control; however, each contaminant has a different solubility

Solubility of Ammonia in Water



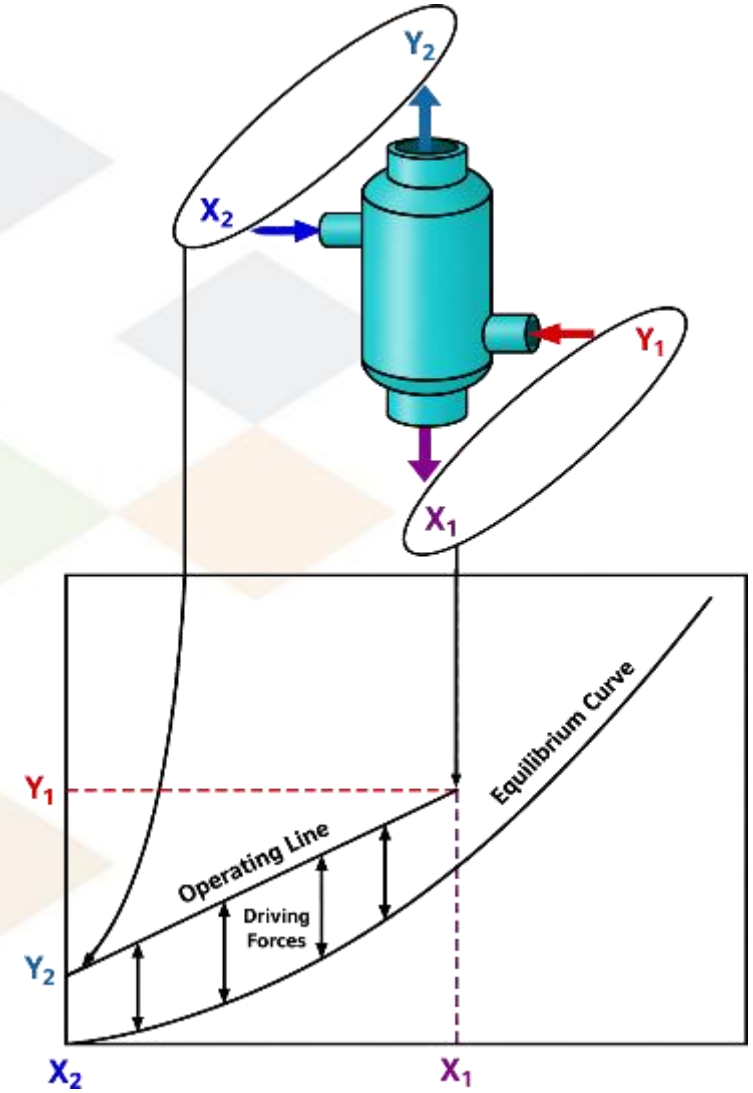
Design Considerations

- **Liquid-to-Gas Ratio**
  - Gallons of liquid per 1,000 standard cubic feet (scf) of gas flow
- **Scrubber Liquid (Solvent)**
  - Need high absorption rate between solute (pollutants) & solvent
  - Need a large supply of scrubbing liquid to operate
    - Water is the most common scrubbing liquid
    - Alkali materials (lime, soda ash, sodium hydroxide) can be added to scrubber liquid to neutralize acid gases
  - Is solvent reused (requires desorption) or disposed?
    - If reused, particulates in scrubbing liquid erode pipes, valves, and nozzles faster

- **Solvent Treatment / Waste**
  - Pollutants in solvent must be removed before solvent disposal / reuse
    - Wastewater standards for oil & grease, biochemical oxygen demand (BOD), and chemical oxygen demand (COD) for VOC in wastewater
    - VOC can be separated from hydrocarbons (oil) by distillation or regeneration by vacuum or heat (stripping)
- **Pressure Differential (Drop)**
  - Difference in pressure between absorber (scrubber) inlet and outlet
    - Higher pressure differential means higher VOC and solvent interaction (capture)

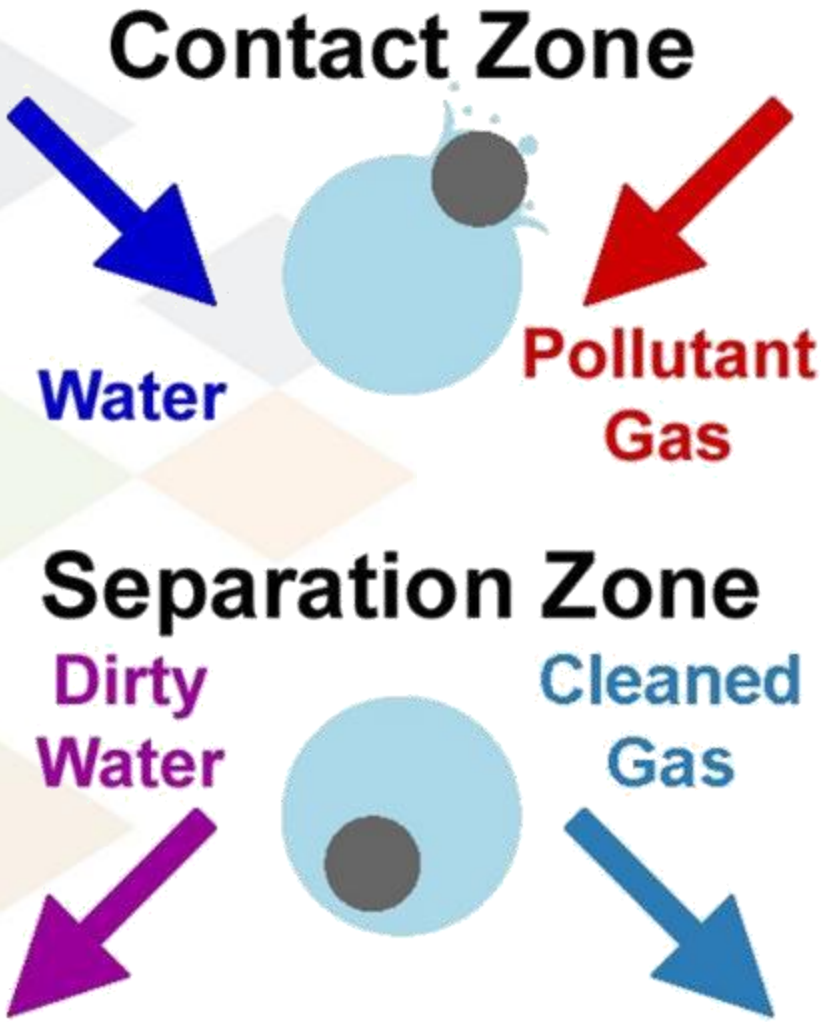
Equilibrium & Operating Lines

- Operating line must be greater than equilibrium curve (gas solubility)
  - X_1: Spent solvent outlet (unknown)
  - X_2: Solvent inlet (may be >0 if using recycled solvent)
  - Y_1: Inlet gas concentration
  - Y_2: Outlet gas concentration (emissions limit)
- Establishes minimum liquid flow



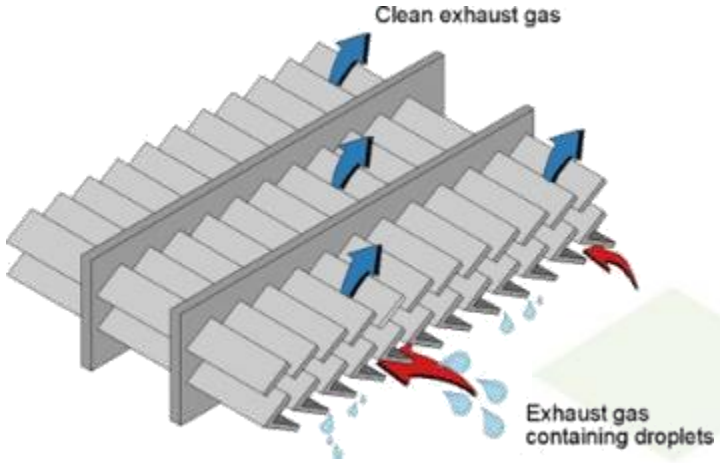
Wet Scrubbers: 2-Part Process

1. **Contact**: Clean (or recycled) scrubbing liquid is mixed with exhaust gases
2. **Separation**: Mist eliminator separates liquids from cleaned exhaust gas
   - Spent (dirty) solvent and mist eliminator droplets removed from exhaust gases for treatment (desorption / discharge / disposal)

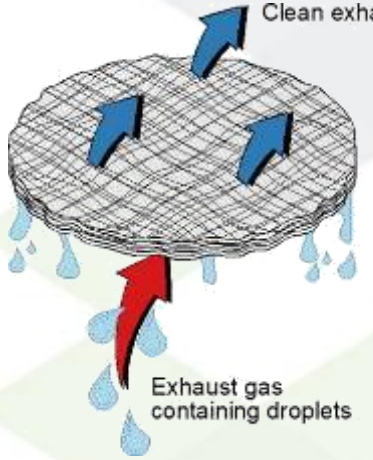


Chapter 5: Absorption
Design Considerations

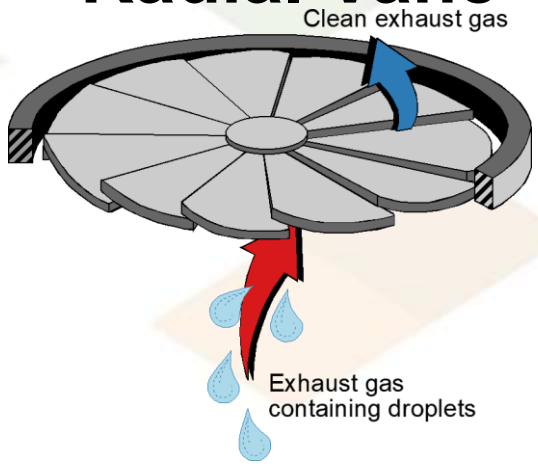
Chevron



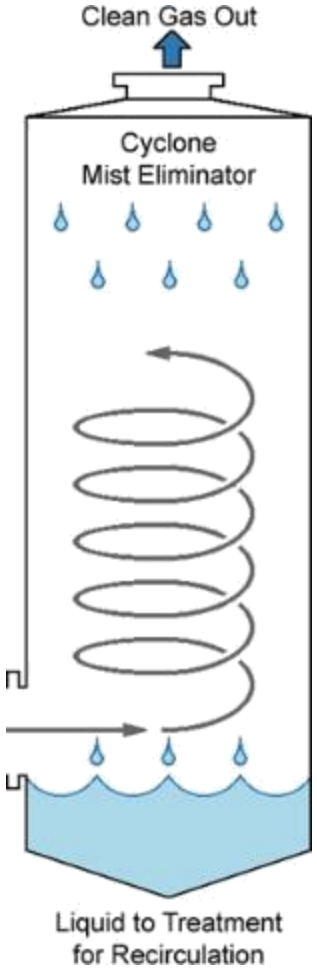
Mesh / Woven Pad



Radial Vane



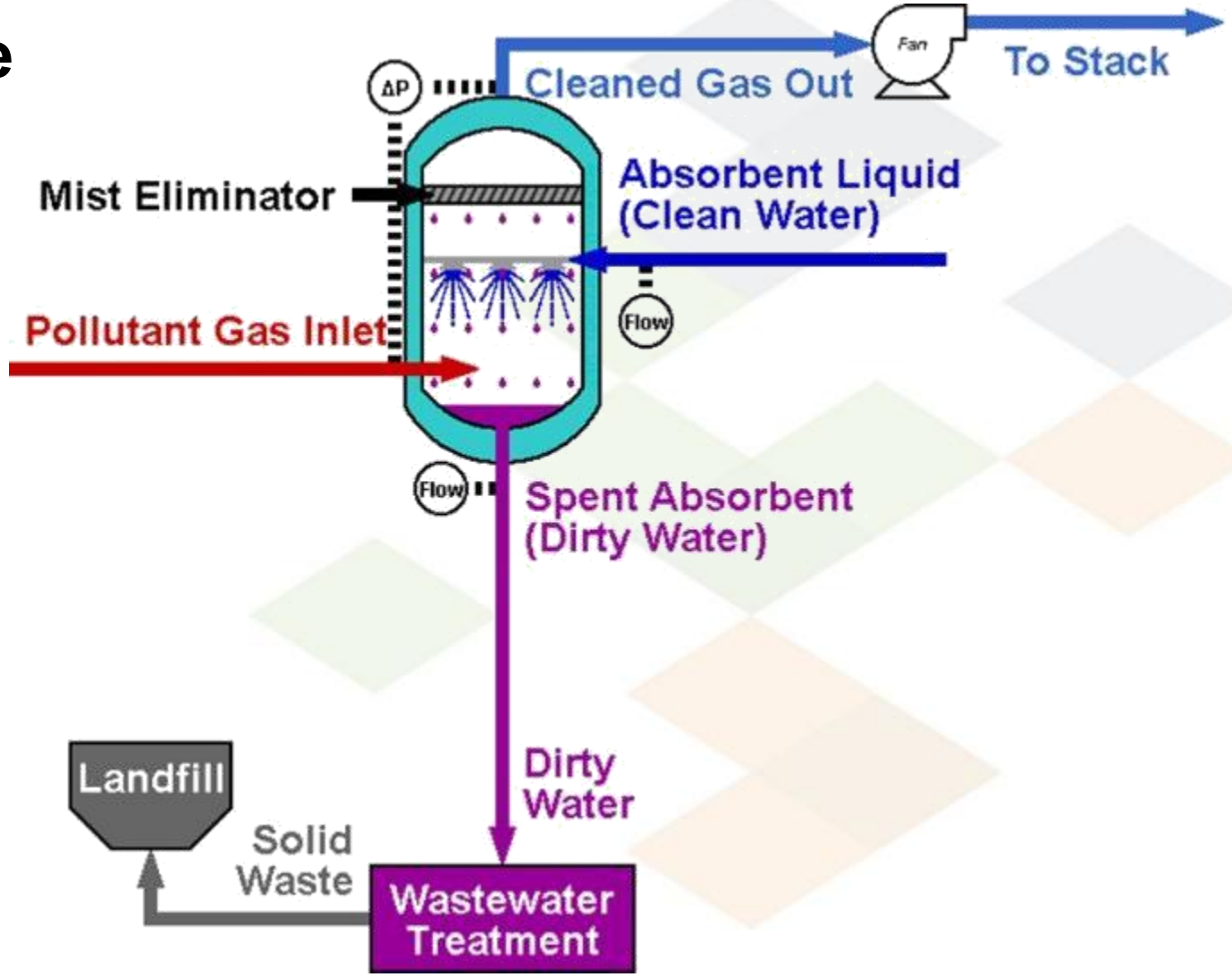
Cyclone



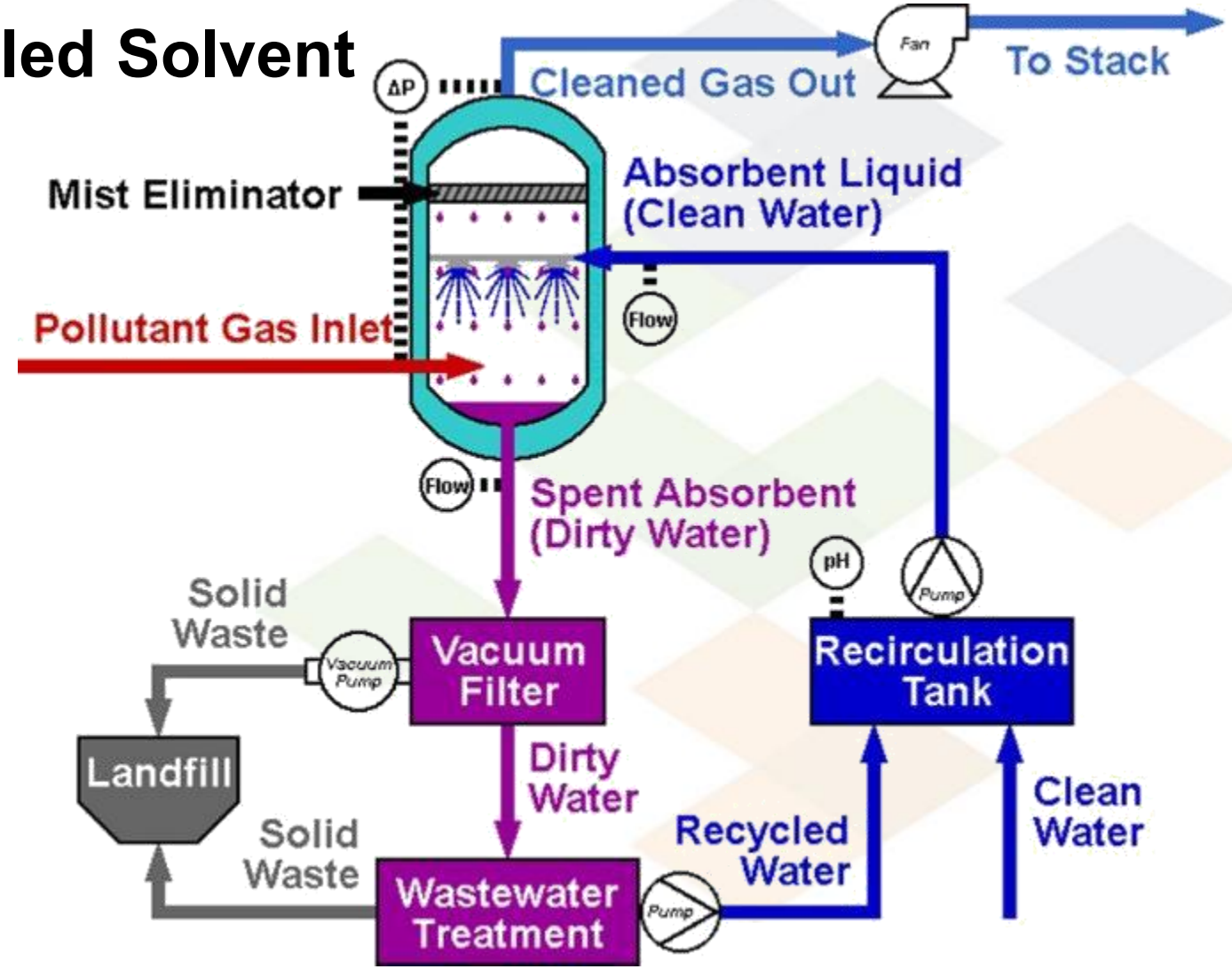
Chapter 5: Absorption
Video

VOC 3.5 - Absorption Mist Eliminator.mp4

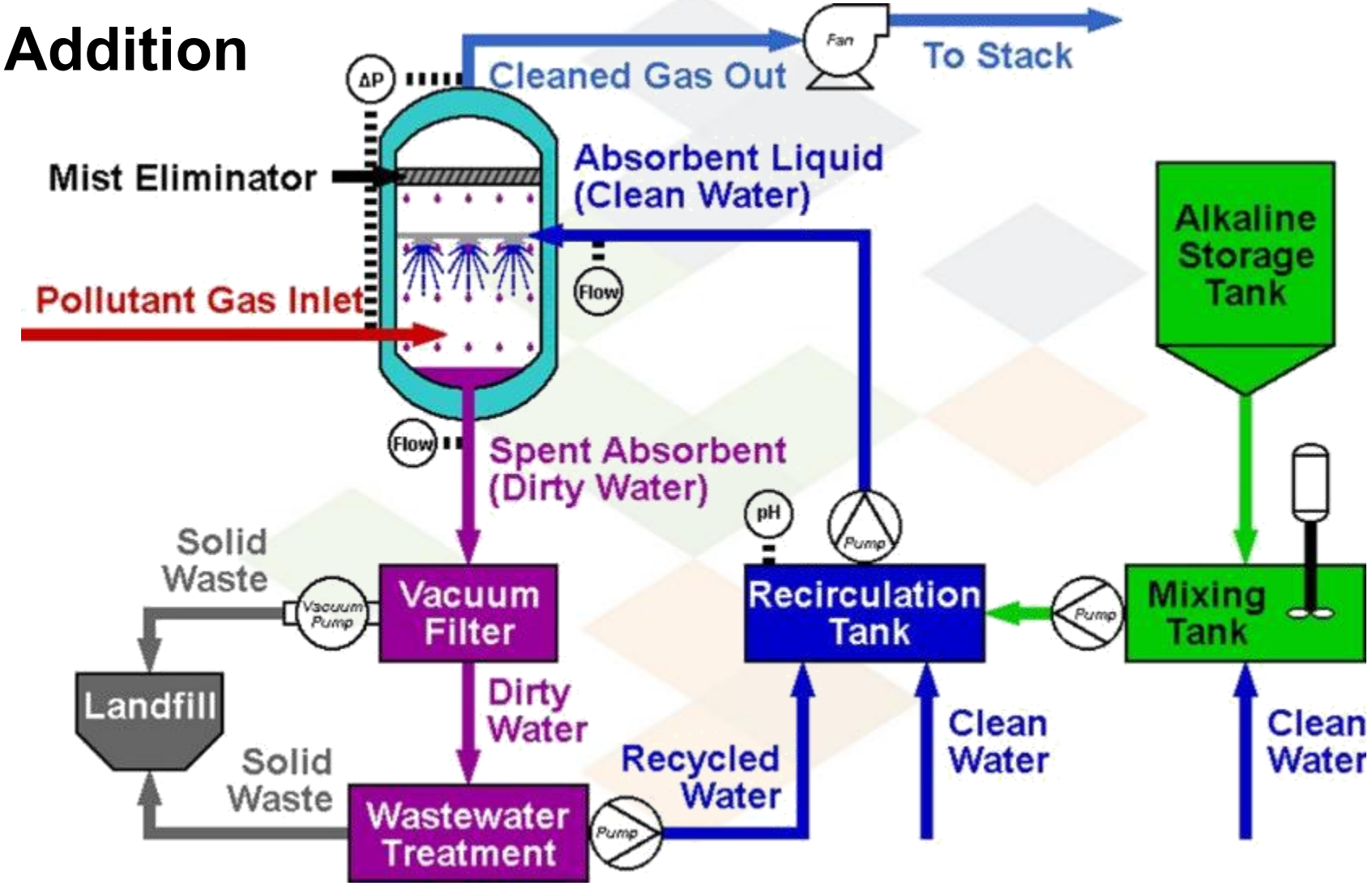
Simple


Fan
To Stack
Cleaned Gas Out
ΔP
Mist Eliminator
Absorbent Liquid
(Clean Water)
Flow
Pollutant Gas Inlet
Flow
Spent Absorbent
(Dirty Water)
Landfill
Dirty
Water
Solid
Waste
Wastewater
Treatment

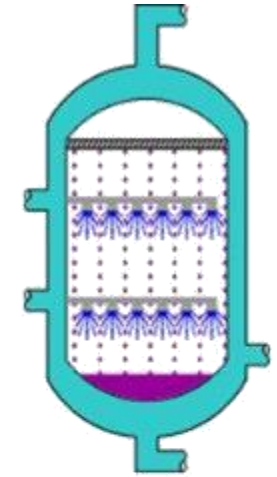
Recycled Solvent



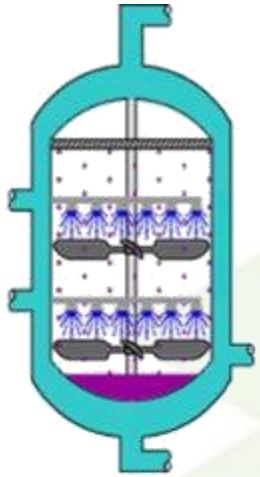
Alkali Addition



Chapter 5: Absorption Controls



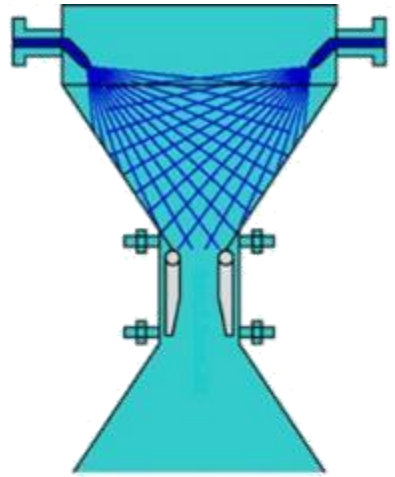
Spray Tower



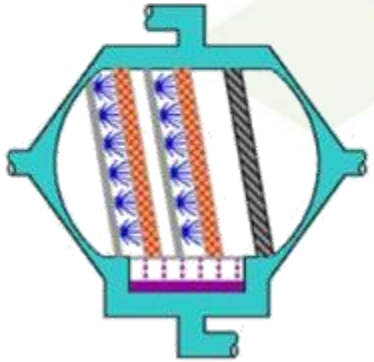
Mechanically Aided



Orifice



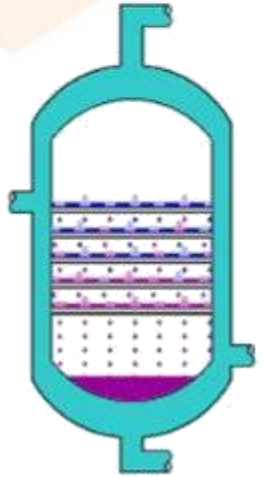
Venturi



Fiber Bed

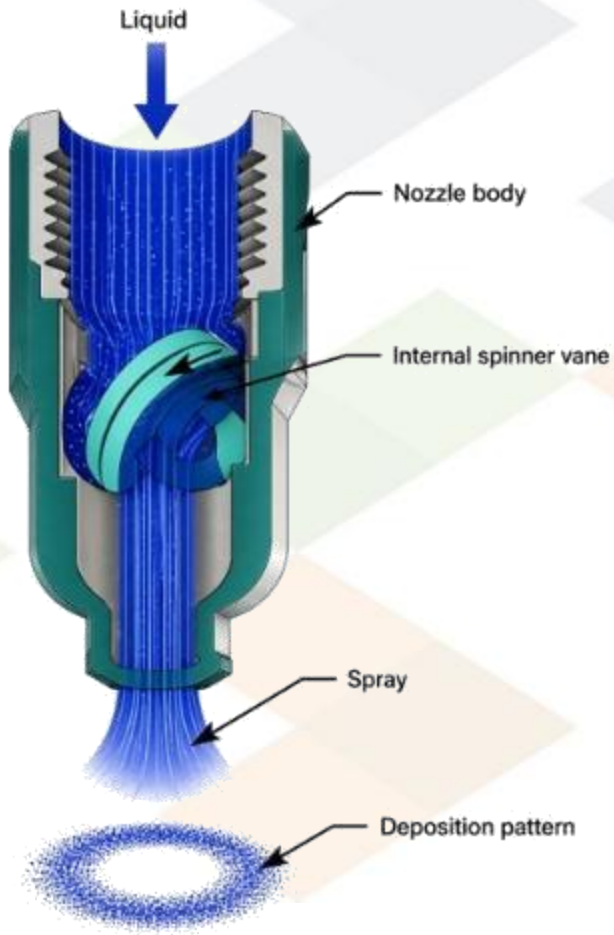


Packed Bed



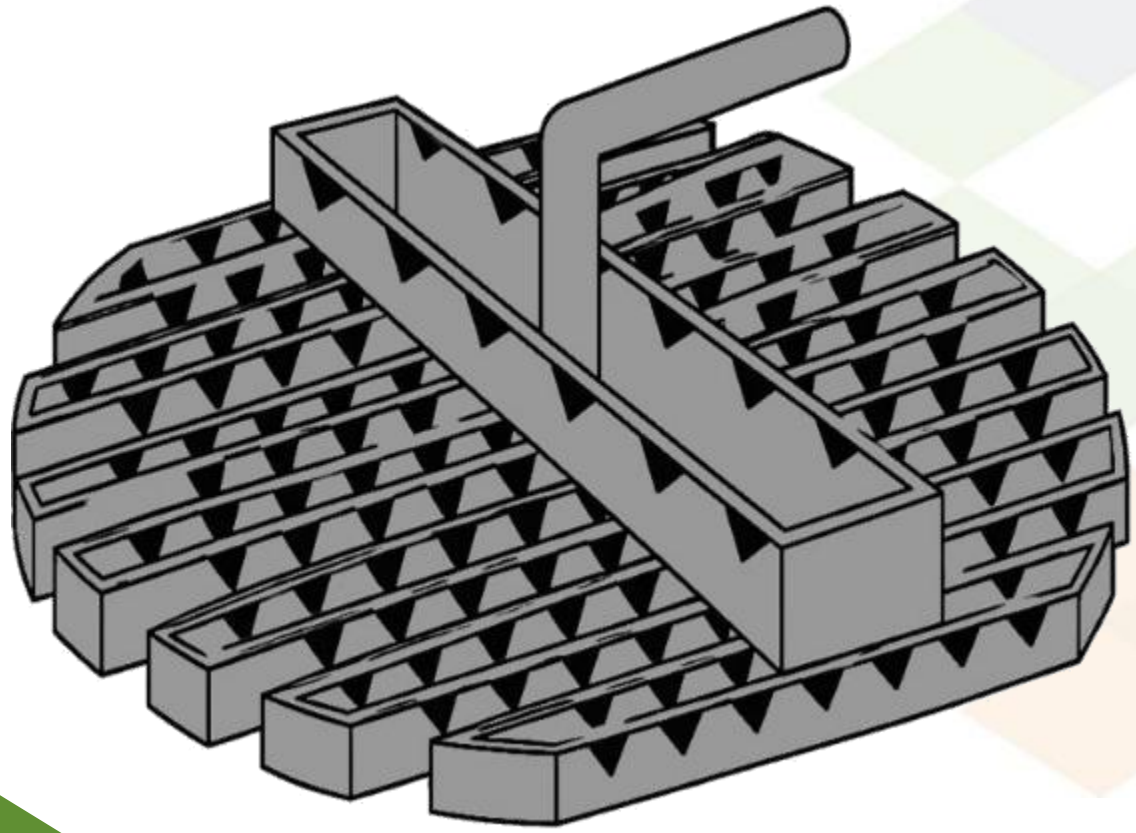
Impingement

Liquid Distributors – Spray Nozzle

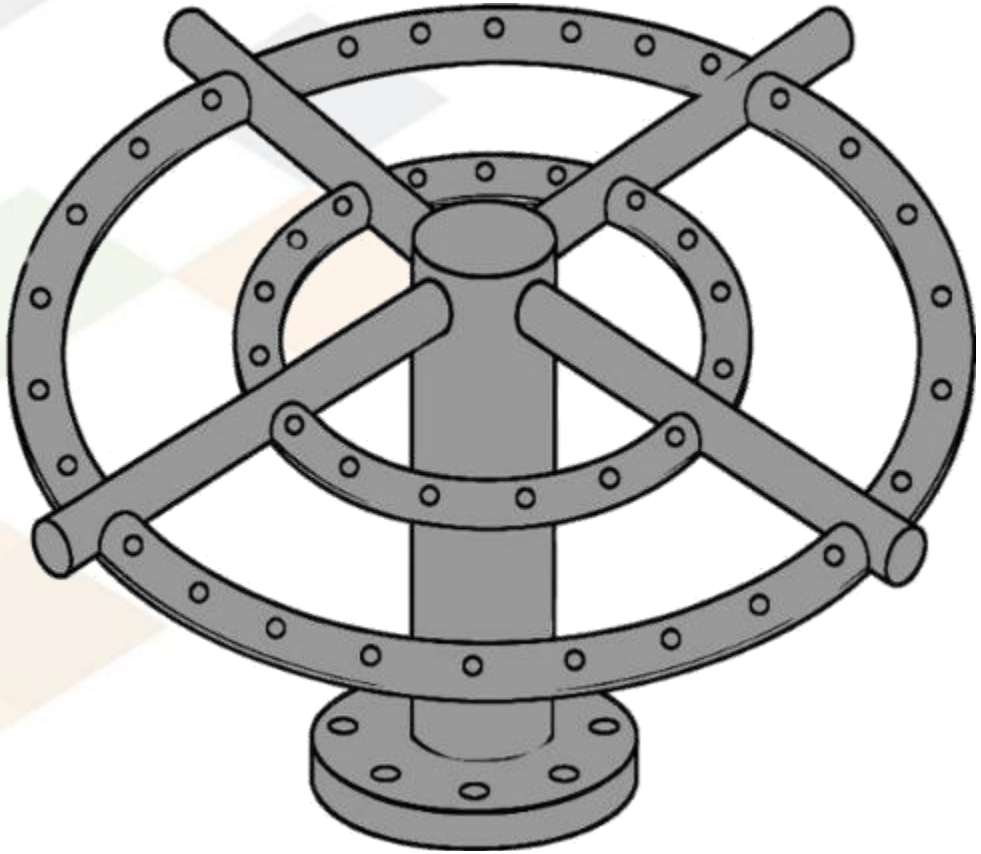


Liquid Distributors

Trough and Weir

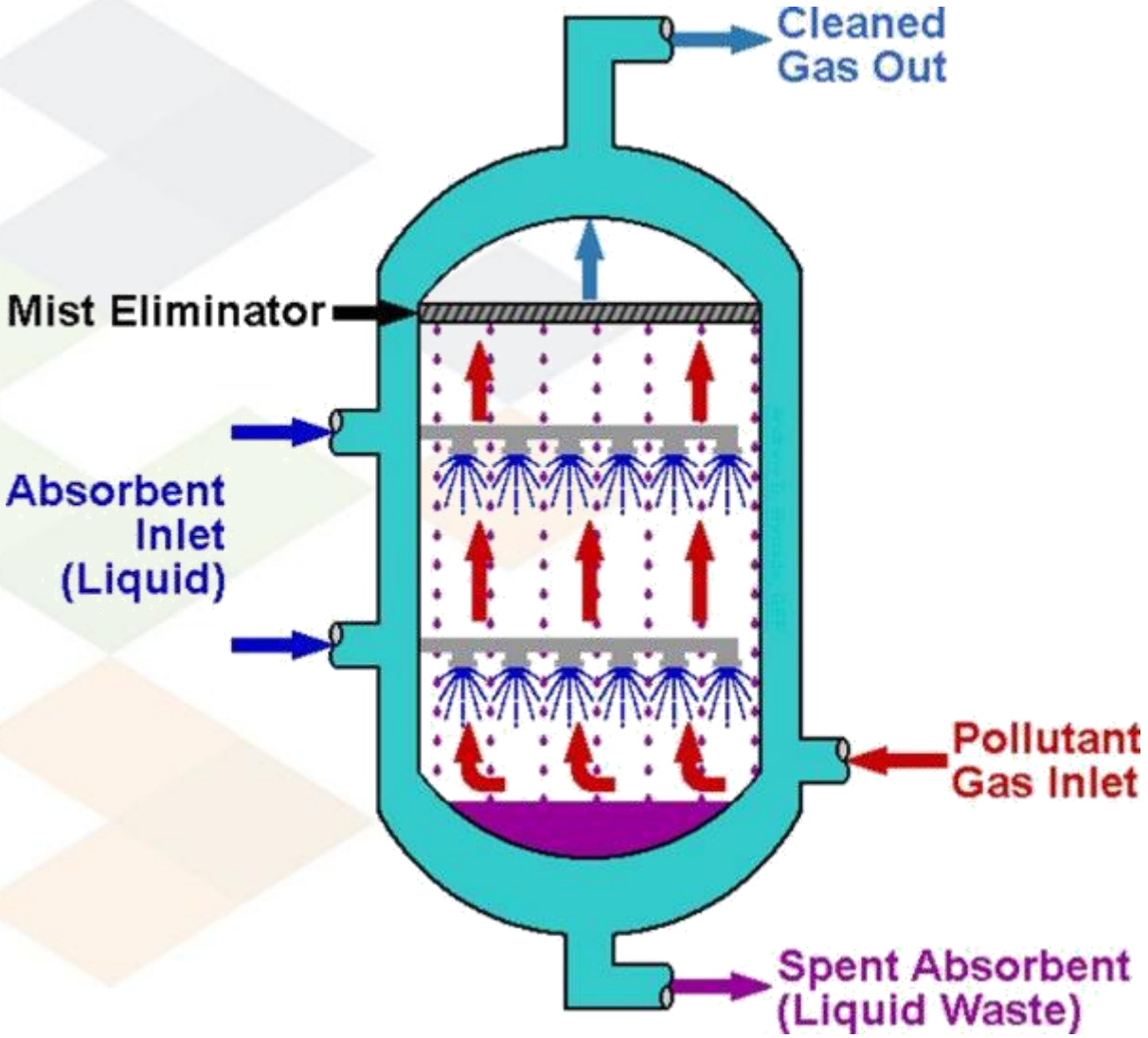


Perforated Pipe



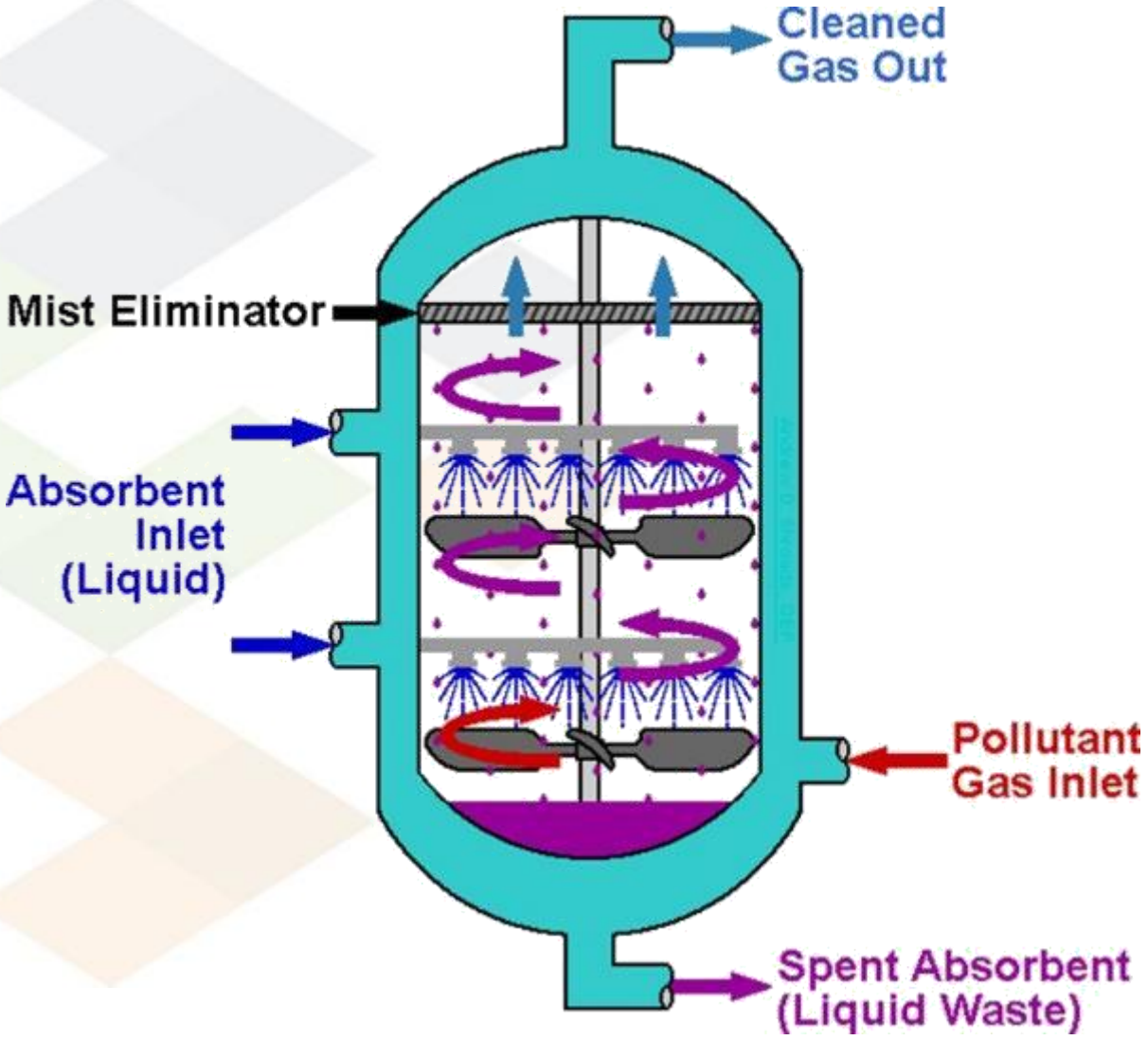
Spray Tower Scrubber

- Spray nozzles generate droplets
  - Relatively large water droplets (500 μm)
- Gas passes upwards, contacting droplets
  - Mainly used for control of soluble gaseous air pollutants with minor PM control



Mechanically Aided Scrubber (Induced)

- Spray nozzles generate droplets
- Rotors induce cyclonic flow (turbulence) for gas to contact droplets
- Relatively high maintenance requirements

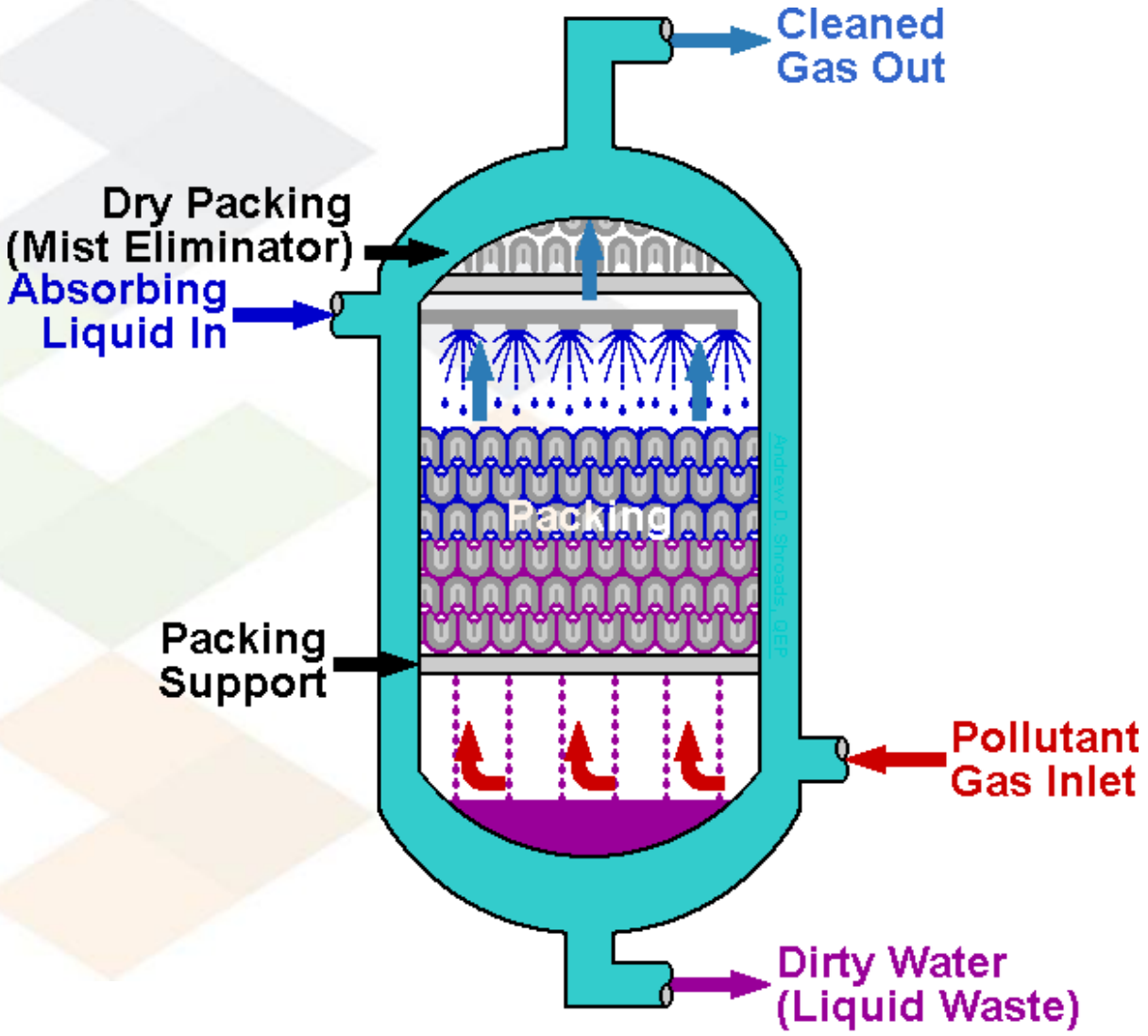


Chapter 5: Absorption
Video

VOC 3.1 - Absorption Spray.mp4

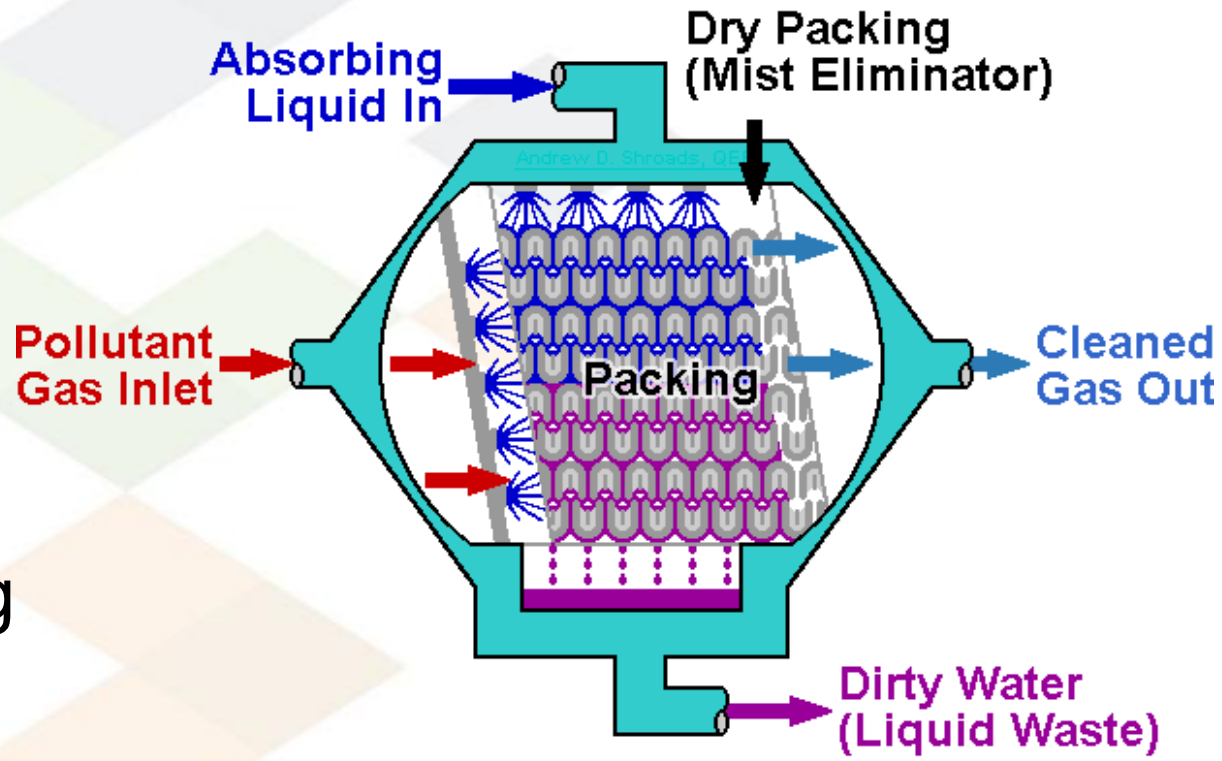
Packed Column Scrubber

- Counterflow: Gas travels upwards, trapping VOC in thin liquid film on packing
  - Limit on upward gas velocity to keep liquid on packing
  - High PM concentration plugs scrubber
  - Mist eliminator usually is last layer of (dry) packing
  - Less soluble compounds require more packing height

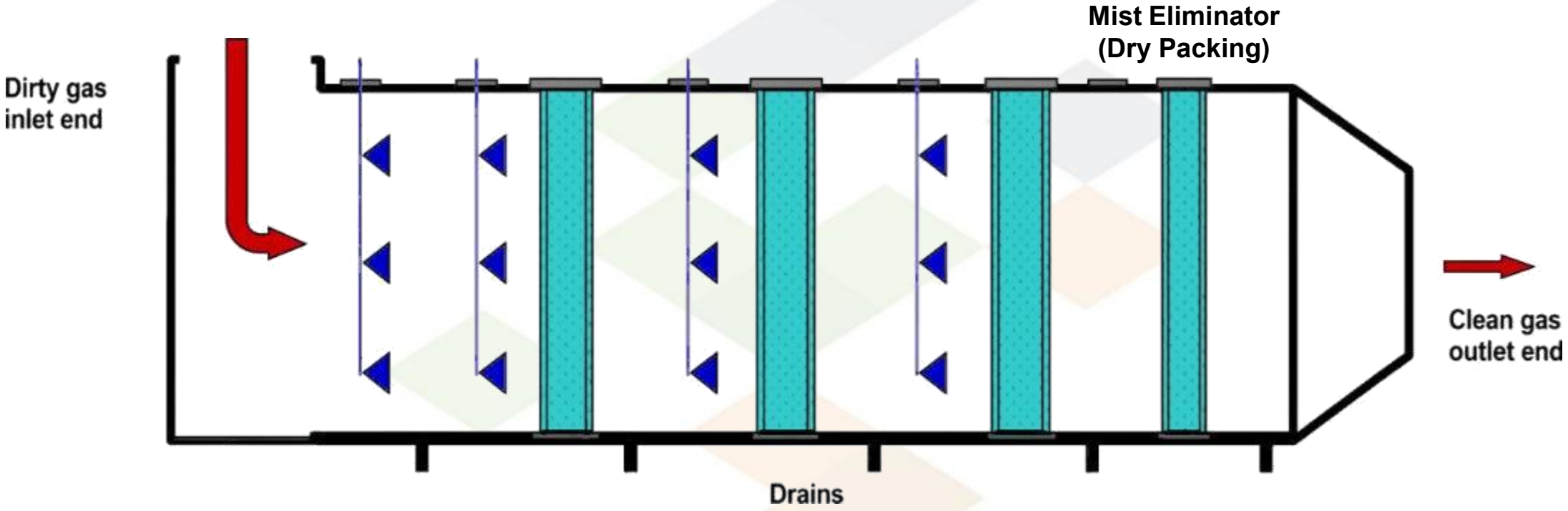


Packed Bed Scrubber

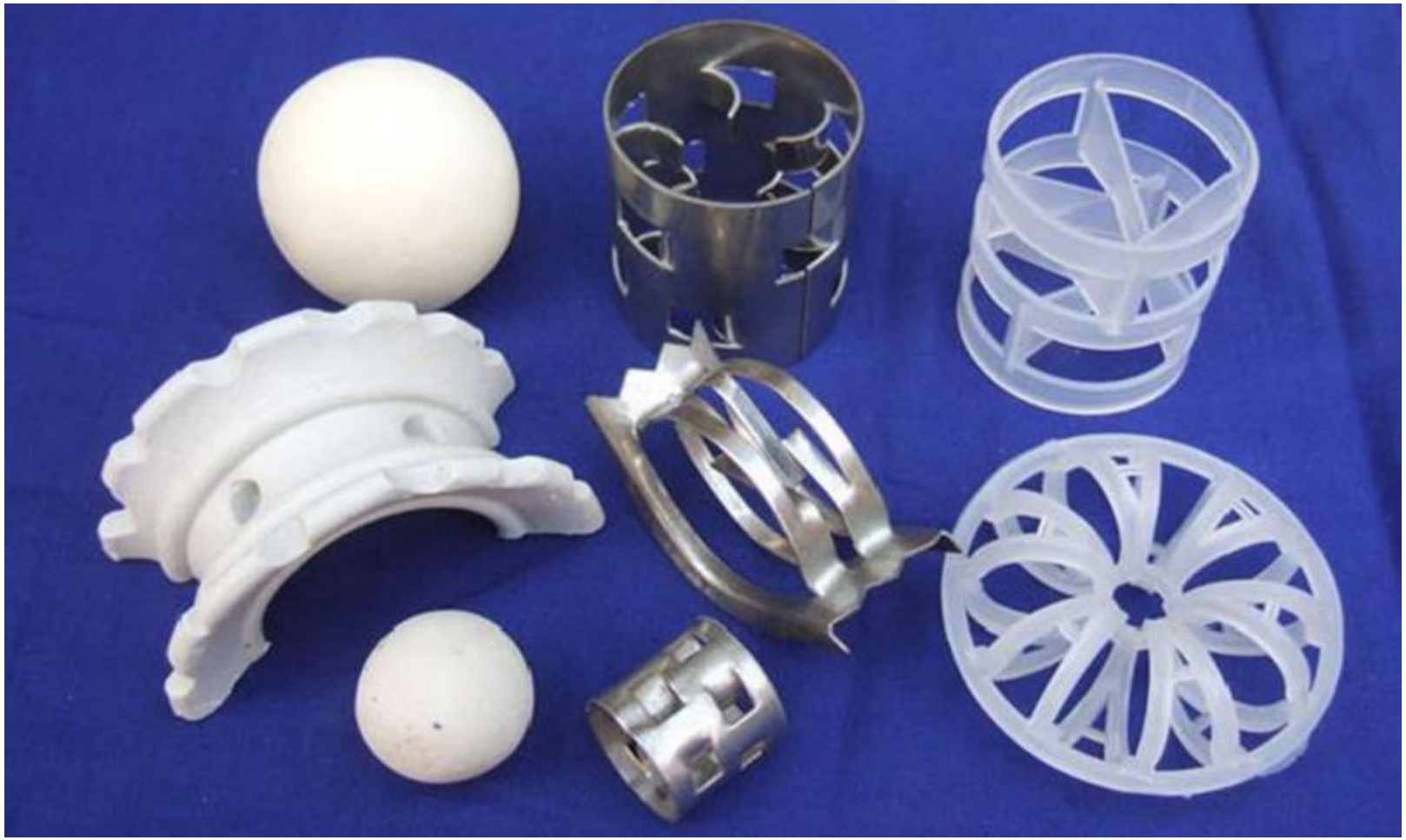
- Crossflow: Gas passes horizontally through scrubber
  - Packing designed to provide largest liquid surface area
  - More common for PM control, not as susceptible to plugging
- Spray nozzles coat packing with thin liquid film
- Dry packing mist eliminator



Crossflow Scrubber

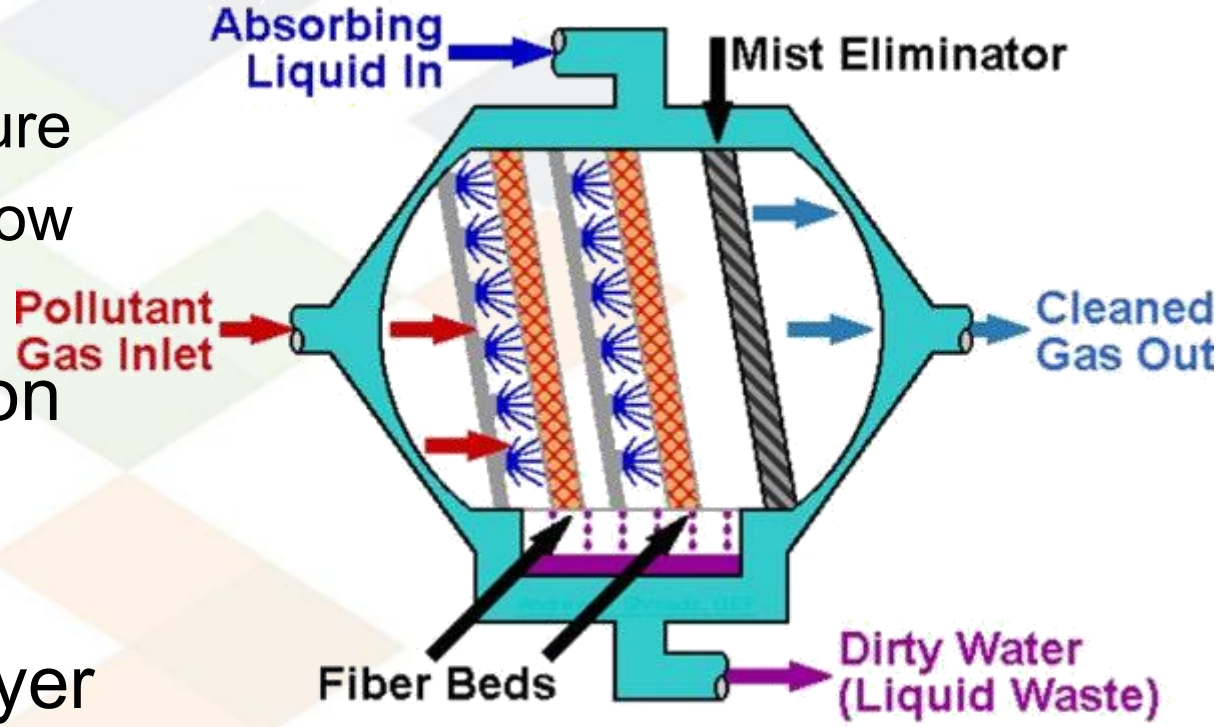


Packed Bed Scrubber Packing



Wetted Fiber Bed Scrubber

- Fabric Filter + Wet Scrubber
  - Mist eliminator as a filter, performing liquid droplet capture
  - Effective for acid vapors and low dewpoint VOC
- Liquid increases retention on and cleans fiber bed
  - Easily becomes plugged
- Mist eliminator: last fiber layer



Chapter 5: Absorption
Video

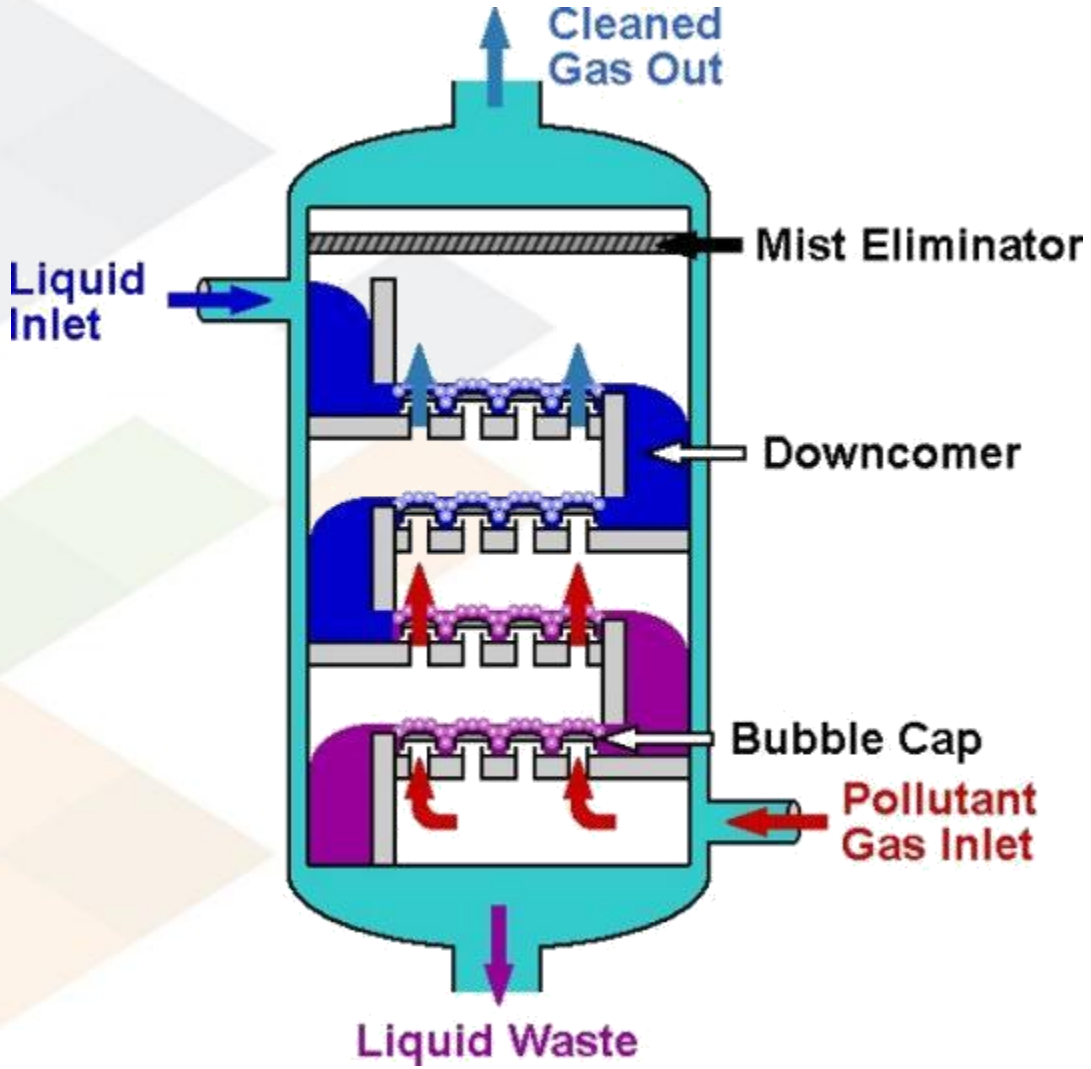
VOC 3.3 - Absorption Packed Bed.mp4

5.2 – Packed Bed Wet Scrubber

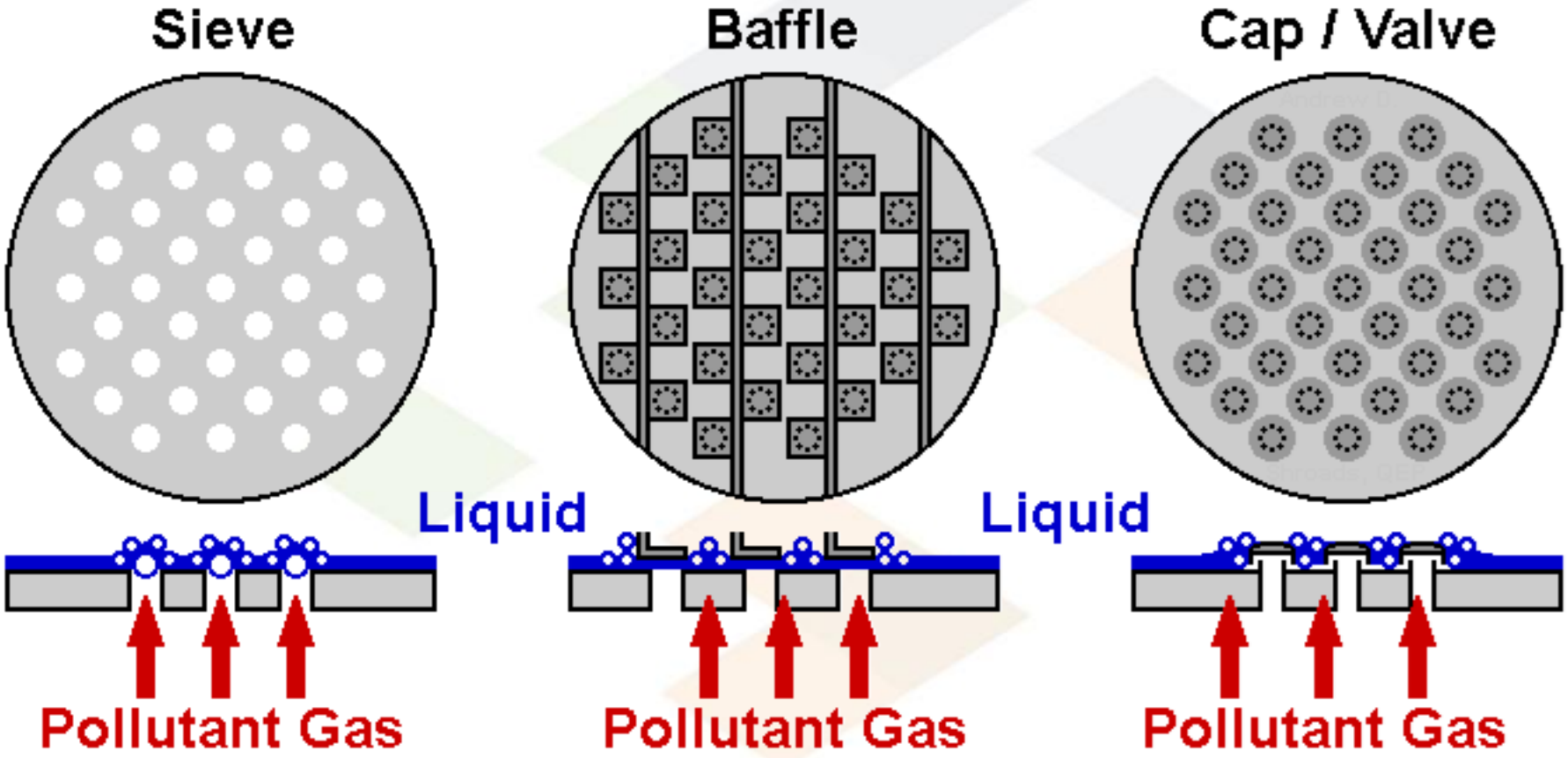
PM 3.4 - Wet Scrubbers Fiber Bed.mp4

Impingement / Tray Scrubber

- Liquid cascades by gravity via downcomers
- Gas rises through tower, forming bubbles
  - Ebullition is bubble formation, providing more surface area
  - Contact between gas and liquid allows absorption to take place
- Tray size based on gas flow
  - Prevent liquid entrainment



Types of Trays / Plates



Impingement Scrubbers

- Column diameter, number of plates, type of plates, plate configuration (layout & spacing)
- Type of plate (cap or valve can respond to variable flow)
- Bubble cap plates spacing
- Particulate loading: susceptible to plugging

Packed Bed & Tray Tower Scrubbers

- To adequately remove contaminants, scrubbers designed with maximum surface area for absorption to occur
  - May need to increase number or size of beds or trays depending on solubility of different gases
  - Trays normally spaced 18-27 inches apart for allowing gas and liquids to separate before next tray and easy maintenance
  - Trays, packing, and mist eliminators have a maximum gas velocity

Chapter 5: Absorption
Video

VOC 3.2 - Absorption Tray.mp4

5.3 – Tray Wet Scrubber

Packed Bed Scrubbers

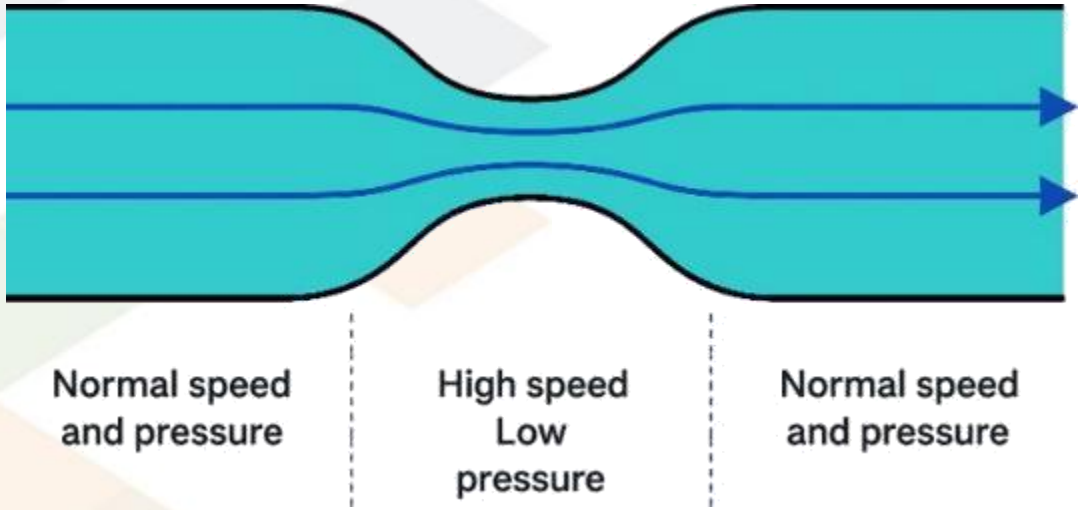
- More common
- Can become plugged by particulate (especially counterflow / tower)
- Better for corrosive pollutants
- Lighter than plate / tray scrubbers

Plate / Tray Scrubbers

- Allow larger temperature changes
- Allow lower liquid flow rates
- Allow variable gas flow rates
- Foaming scrubbing liquids
- Chemical reactions between solvent and exhaust gas
- Larger systems

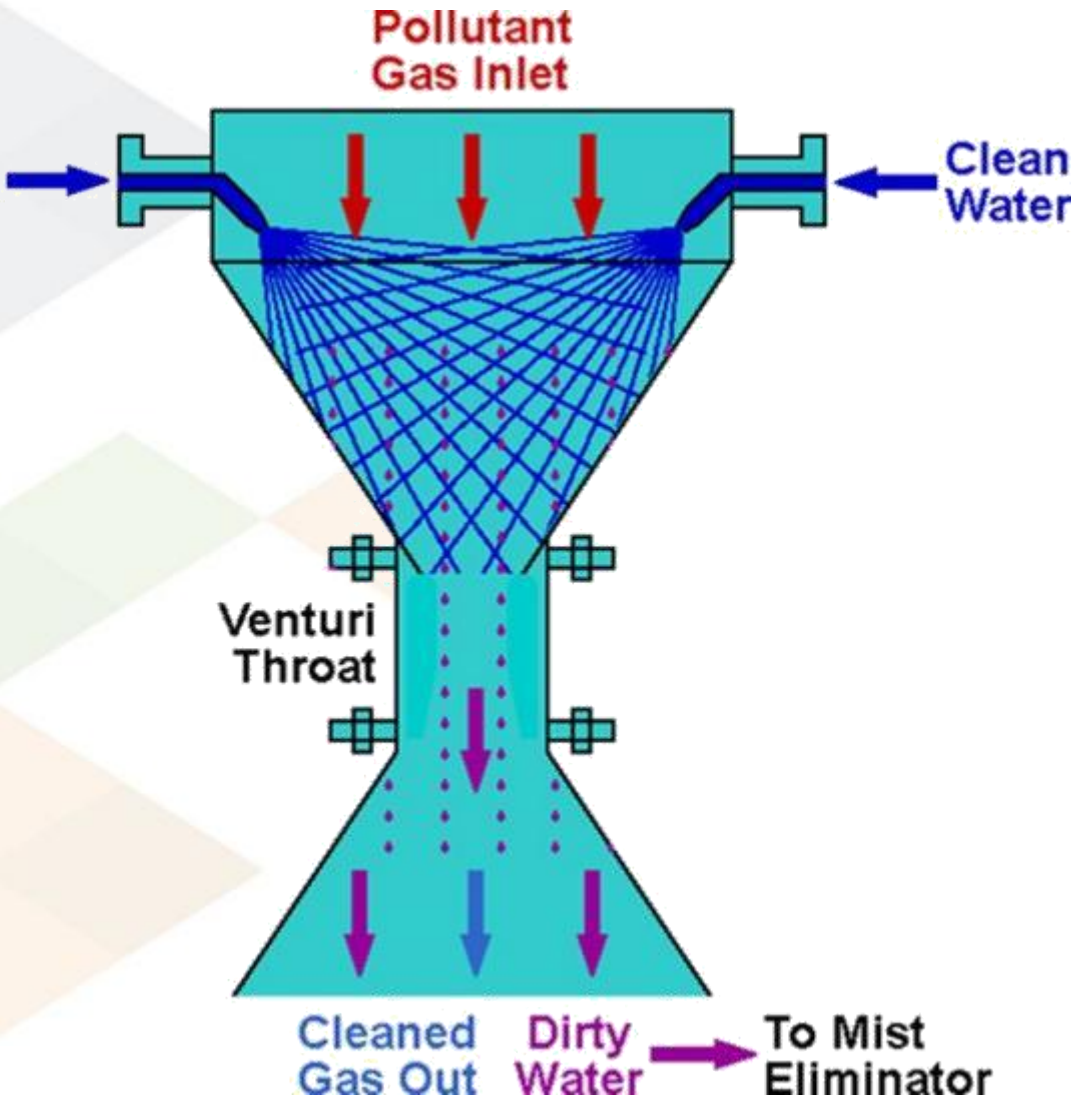
Venturi Wet Scrubber

- Narrowing duct size (throat) increases air speed
  - To keep the same air flow rate, air speeds up in throat
  - Higher air pressure before throat
  - Lower air pressure inside throat can pull in scrubbing liquid
- Mostly used for PM control
  - Depends on solvent solubility for other pollutants



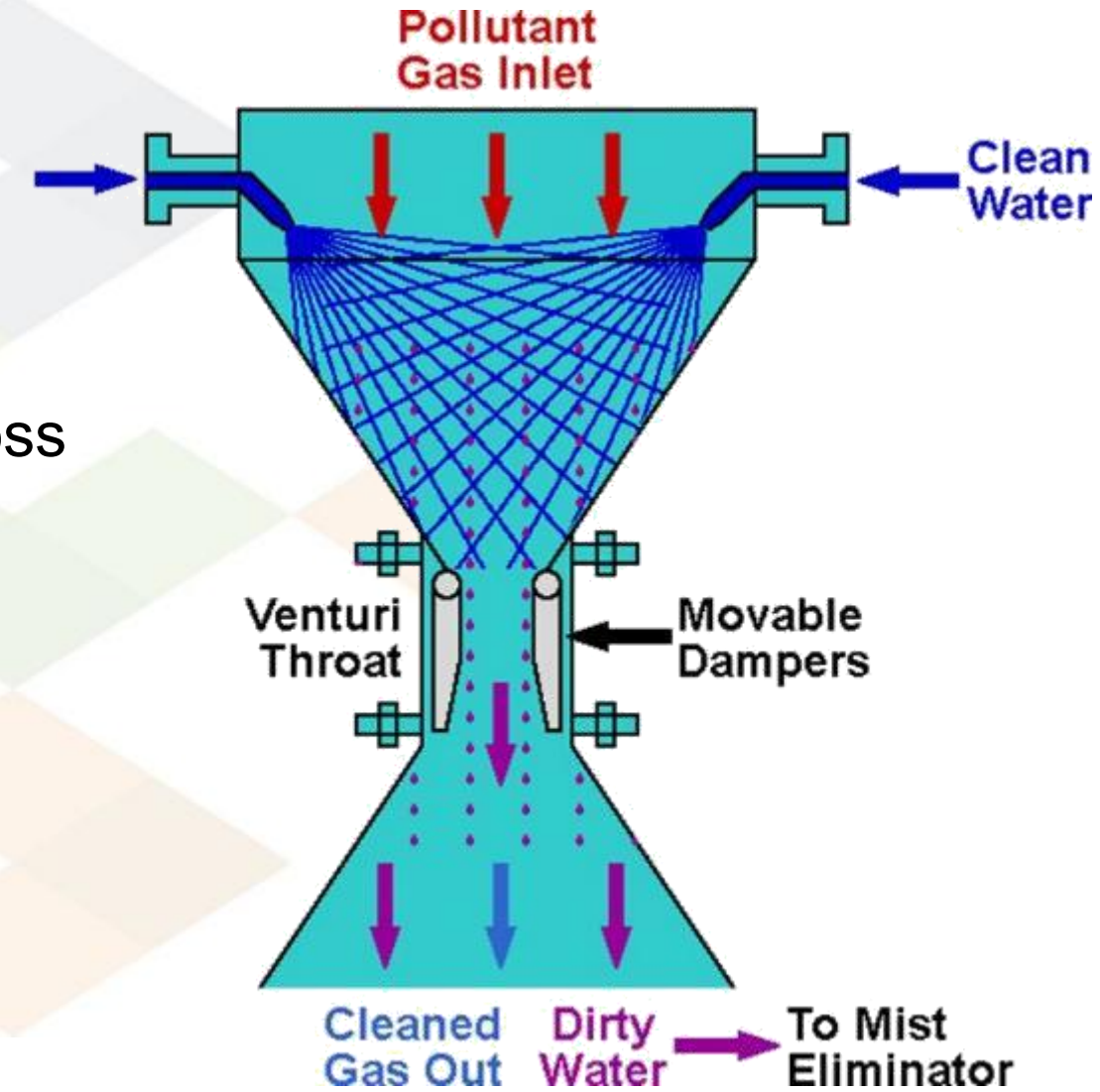
Fixed Throat Venturi

- Inlet gas accelerated to 300 – 600 feet per second at venturi throat
  - Liquid droplet size 50 – 75 µm
- High relative velocity atomizes liquid to promote particle impaction onto droplets
- Continuous inlet gas flow rate



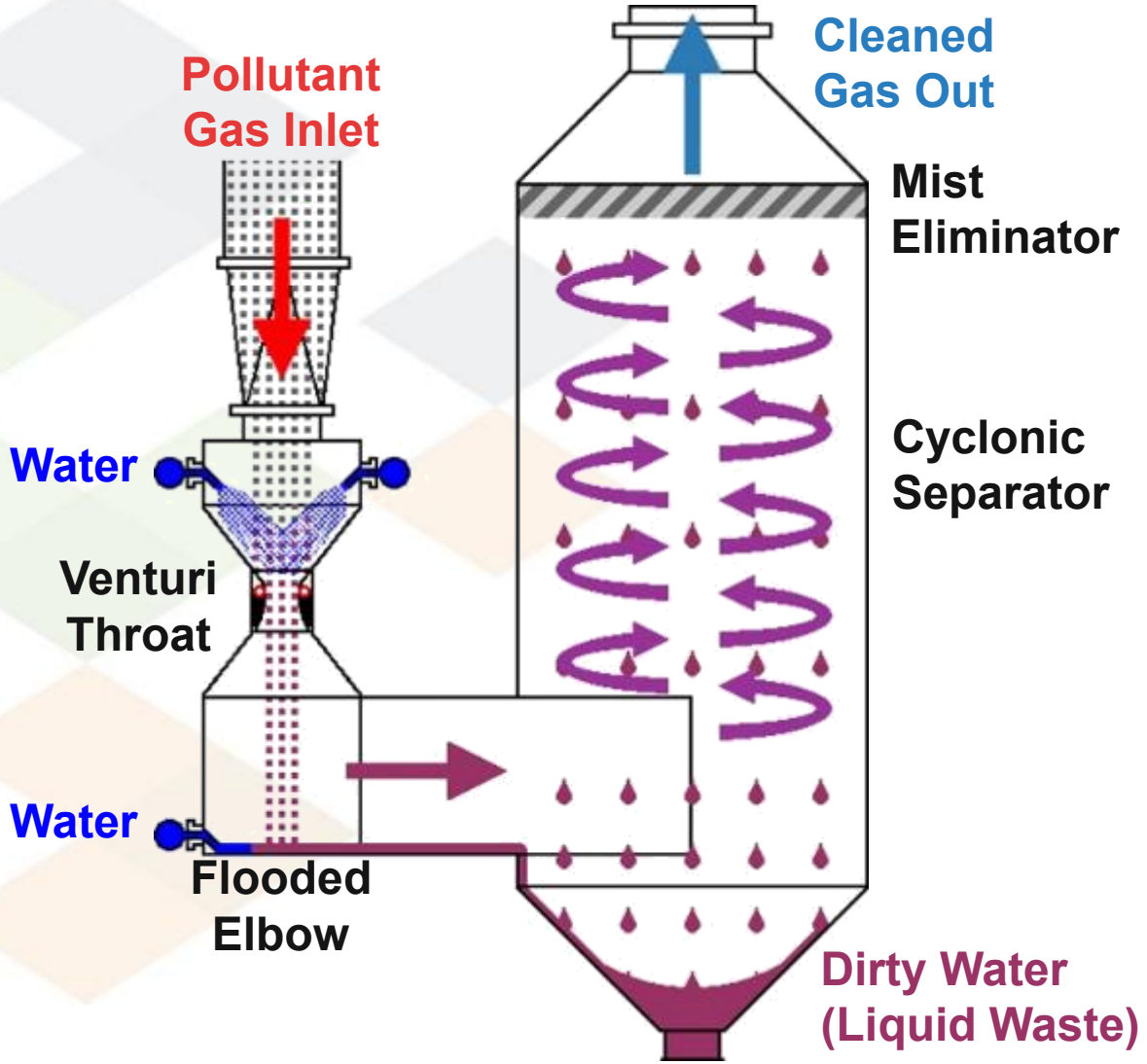
Adjustable Throat Venturi

- Better control for variable inlet gas flow rate
  - Dampers can be set to maintain a constant pressure differential across venturi throat
  - Higher pressure drop, better collection efficiency
- Throat dampers are subject to ***extreme*** abrasion



Venturi Scrubber

- Walls, throat, and bottom of venturi usually wetted / flooded to reduce abrasion
- Significant mist elimination to remove spent solvent
- Large quantities of spent solvent (wastewater) are generated and require recycling or treatment (for disposal)



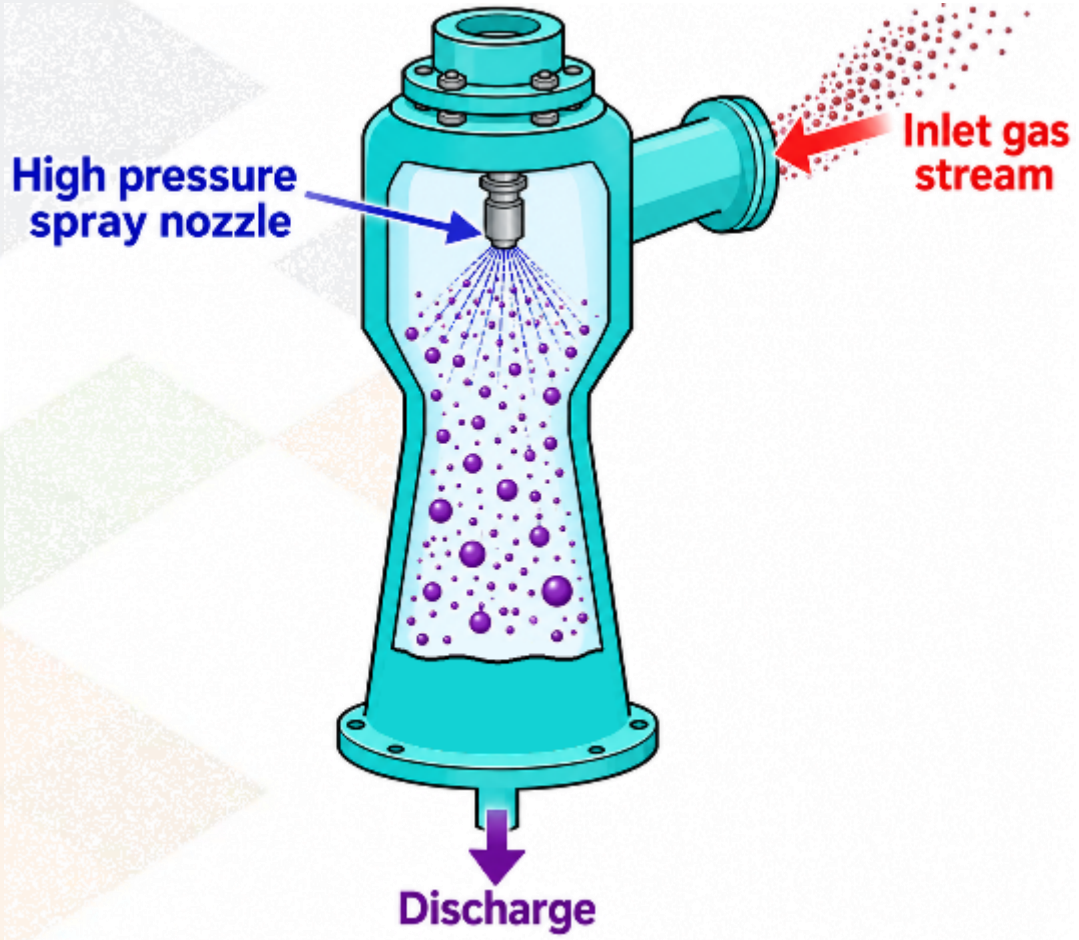
Chapter 5: Absorption
Video

PM 3.5 - Wet Scrubbers Venturi.mp4

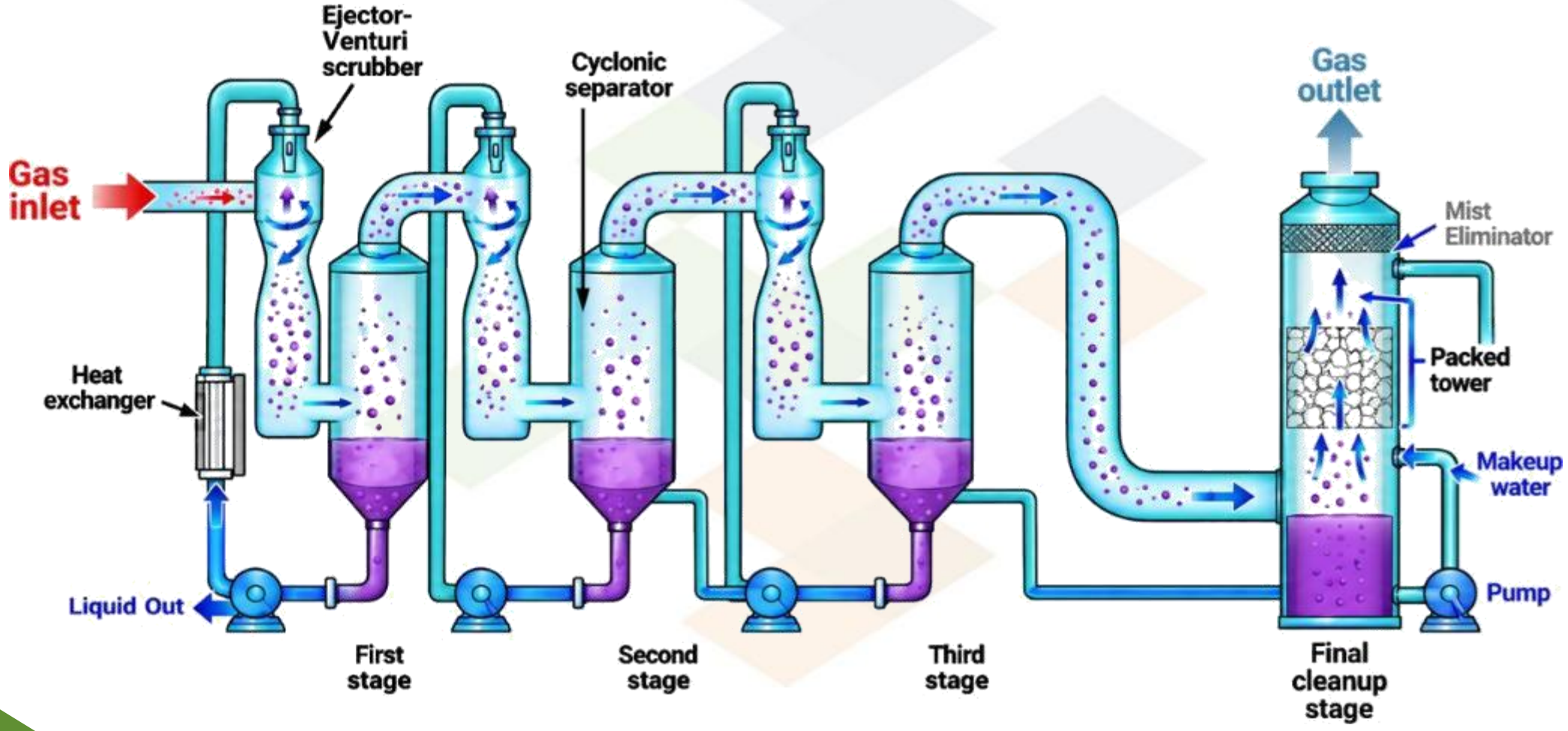
5.4 – Venturi Wet Scrubber

Ejector Absorbers

- Liquid added to ejector through high-pressure spray nozzle operating at >80 psig
- Liquid creates an aspiration effect that pulls the gas through the vessel and eliminates the need for a blower (fan)
  - Suction must be large enough to overcome gas resistance



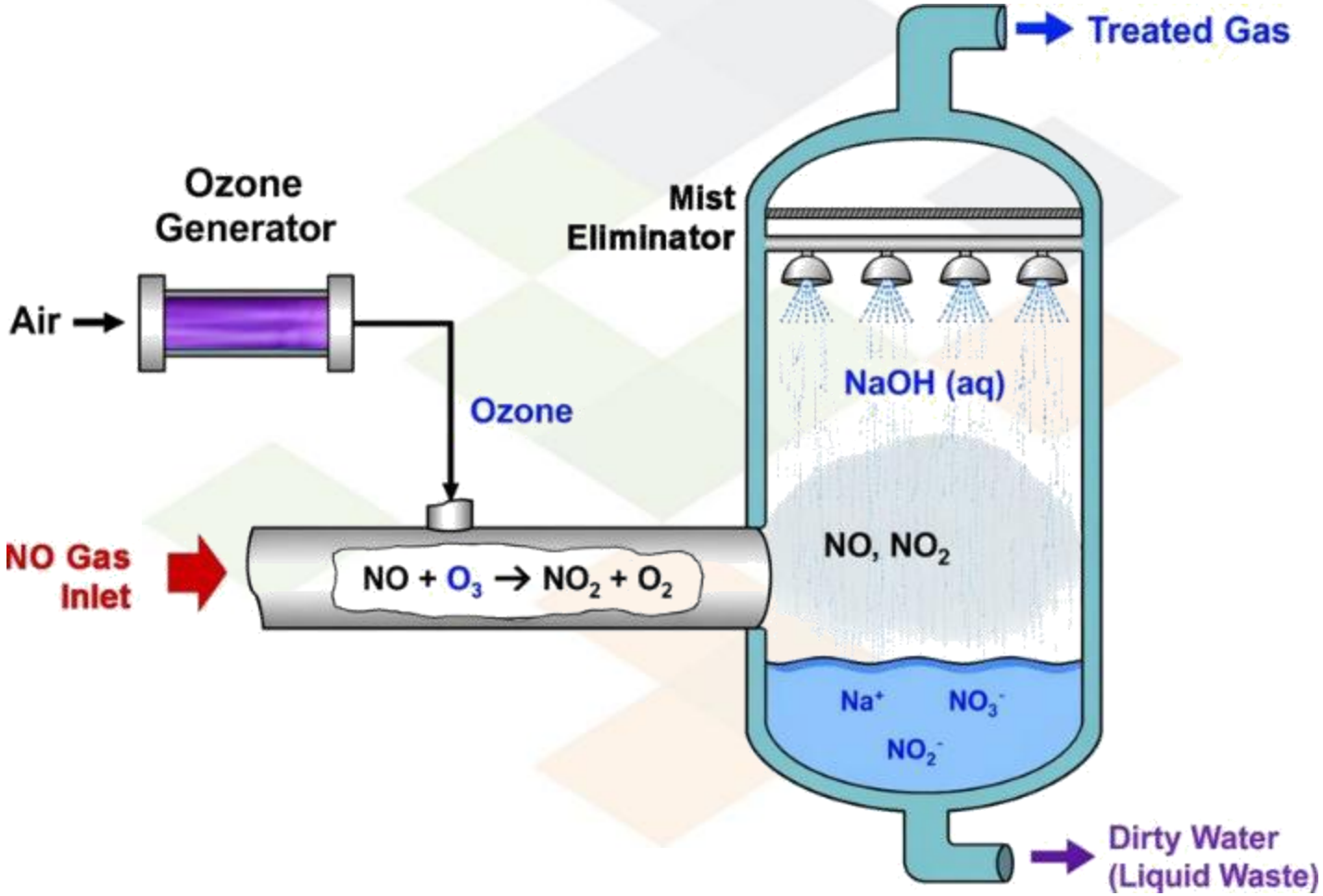
Ejector Absorber (Series) & Cyclone Mist Eliminators



Chemical Absorption – NO_X

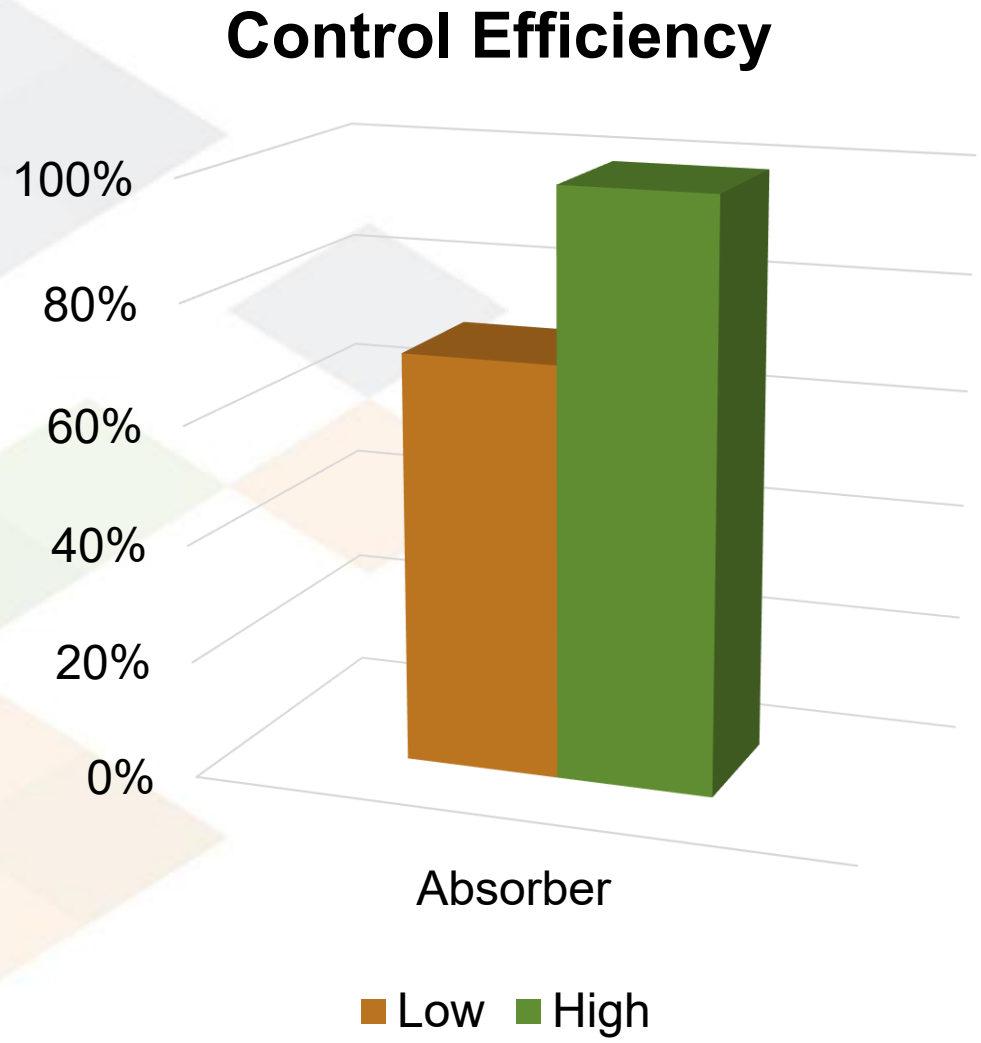
- NO is very poorly soluble in water, so it must be converted to a water soluble compound via a multistage process
  1. Oxidation: NO / NO_2 converted to NO_3^-, which is more water soluble, using an oxidizer in a basic (alkaline) solution or via ozone injection
  2. Absorption: NO_3^- reacts with water to form HNO_3 (nitric acid)
  3. Neutralization: After absorption, more alkali added to form insoluble nitrate salts and treat scrubber liquid
- Requires multi-stage scrubber and wastewater treatment

Chemical Absorption – NO_X



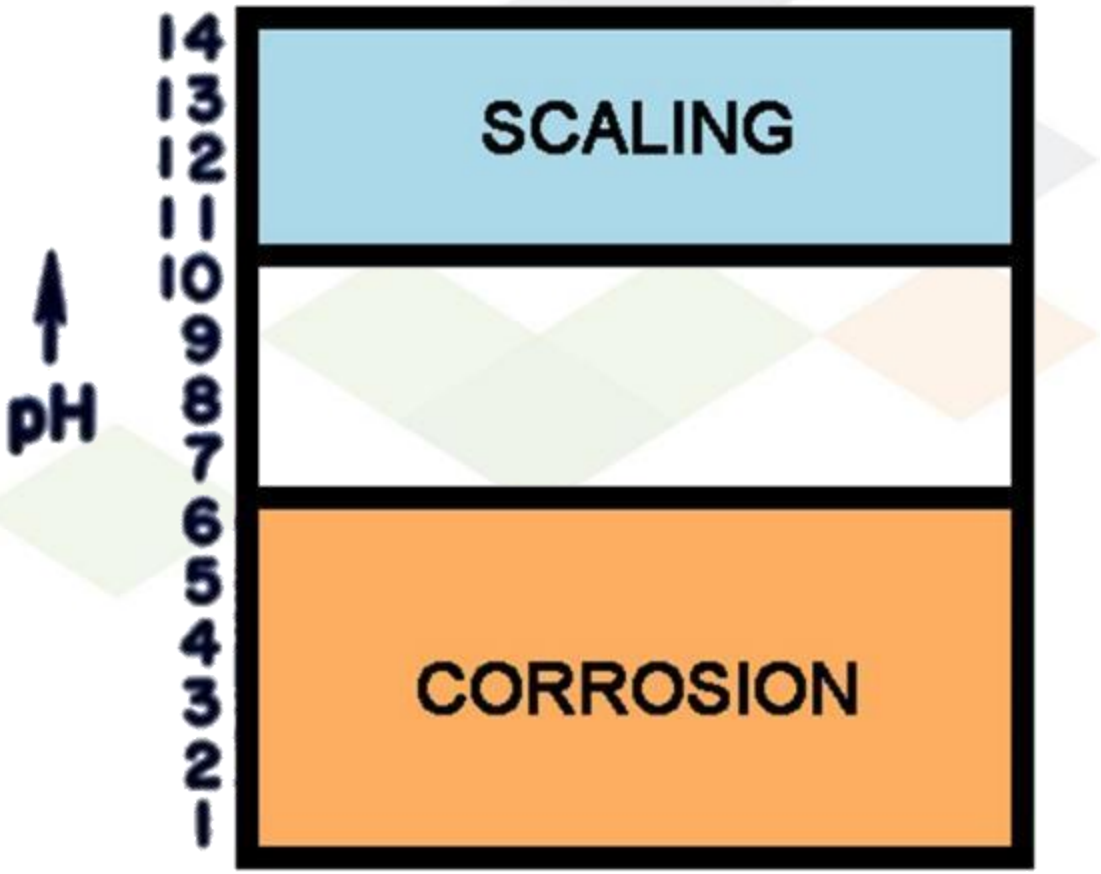
Control Efficiency

- 70-99%
- Solvent (scrubbing liquid) must dissolve or react with the pollutant (solute)
- Alkaline may be added to react with acid gases



- **Liquid Recirculation**
  - Inadequate liquid flow lowers control efficiency
- **pH**
  - Alkali feed rate needs to be sufficient to neutralize acids
  - Scaling: If pH is too high (basic), scale can build up in pipes & scrubber
  - Corrosion: Acid gases, particulate, and water at high pressures can corrode pipelines and scrubber shell
- **Droplet Re-entrainment**
  - Solids buildup on or damage to the mist eliminator
  - Ice buildup on exhaust stack
  - High gas velocity

Deposits (Scaling) or Corrosion by pH



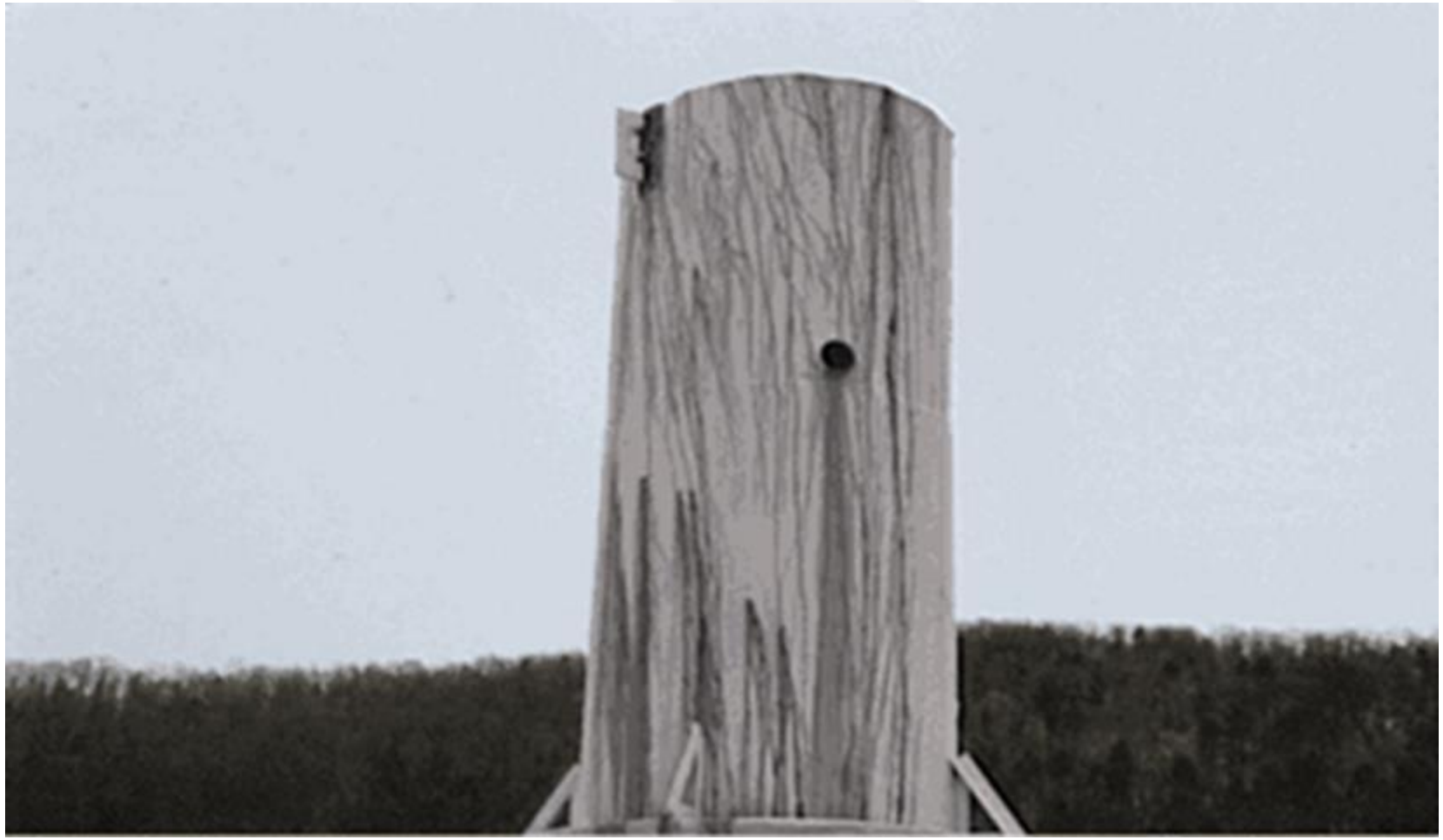
Mist Eliminator Plugging – Example



Corrosion: Leaking Components - Example



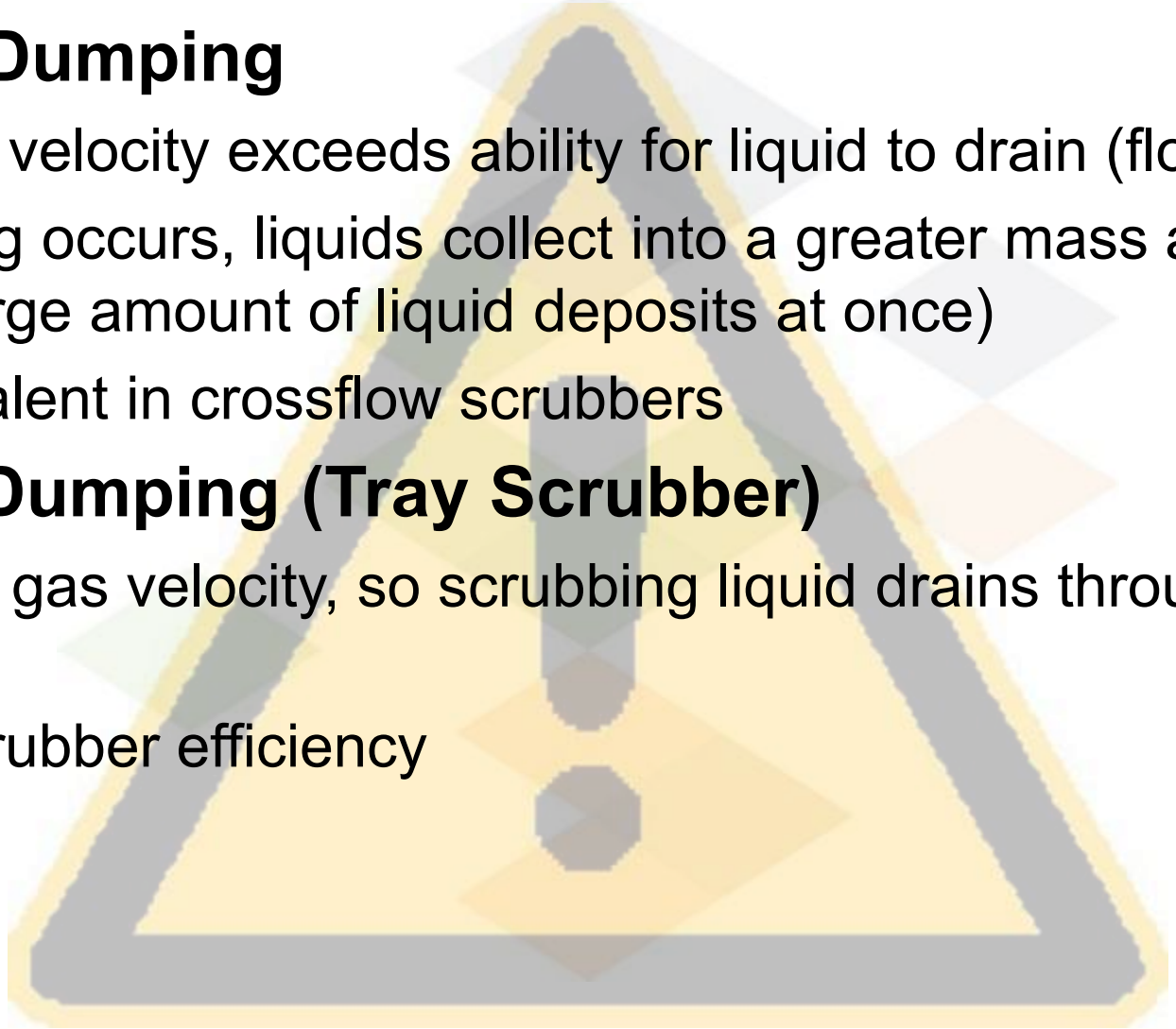
Droplet Re-Entrainment – Example



Operating Problems

- **Plugging**
  - Tower scrubbers are susceptible to plugging (clogging) by PM
  - Build up of PM can plug nozzles, trays, and mist eliminators
  - Nozzle plugging (especially if recirculated) affects solvent distribution
  - Exterior units can freeze during the winter
  - Parametric monitoring ports can also become plugged
  - Dissolved minerals / solids in solvent buildup as scale (plugging)
- **Byproducts are hard to recover**
  - Solvent recycling is not completely effective (some pollutants remain)
  - Rely on desorption or wastewater treatment system

- **Flooding / Dumping**
  - Upward gas velocity exceeds ability for liquid to drain (flooding velocity)
  - After flooding occurs, liquids collect into a greater mass and cause dumping (large amount of liquid deposits at once)
  - Not as prevalent in crossflow scrubbers
- **Weeping / Dumping (Tray Scrubber)**
  - Low upward gas velocity, so scrubbing liquid drains through sieves / baffles
  - Reduces scrubber efficiency



- **Packed Bed Scrubber:**
  - Inadequate liquid distribution reduces control efficiency
  - Channeling: liquid tends to flow to outer walls, allowing exhaust air to create tunnels in absorbent
    - Limit packed bed diameter & height (<10 feet) or add liquid distribution
    - May not be indicated on packed bed pressure differential
  - Bed collapse: packing material shift or breakdown, dropping through support grid, creating severe channeling
    - Corrosion of support grid or material packing
    - Increased weight due to salt formation or PM
    - Change in packed bed pressure differential may indicate bed collapse

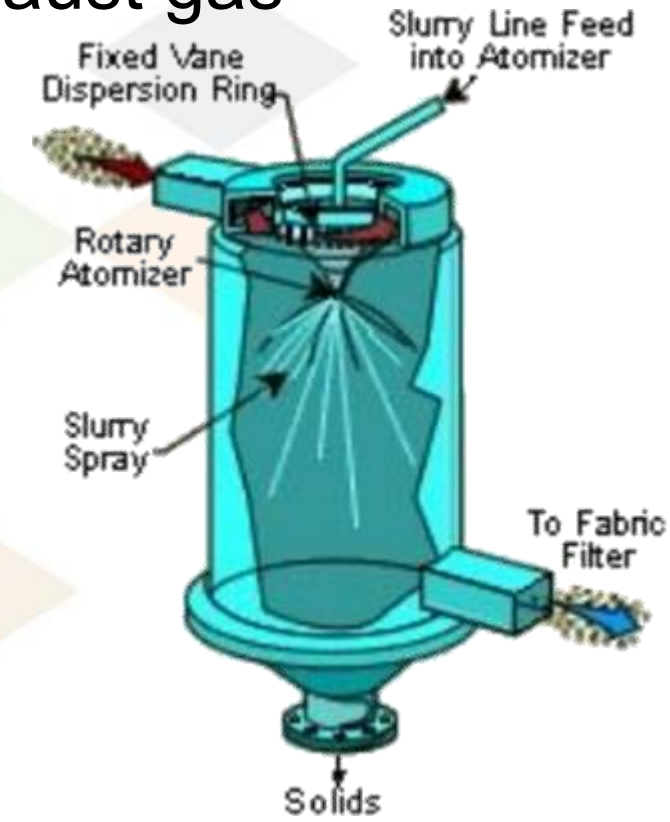
Wet Absorber (Scrubber)

- Liquid sprayed directly onto exhaust gas

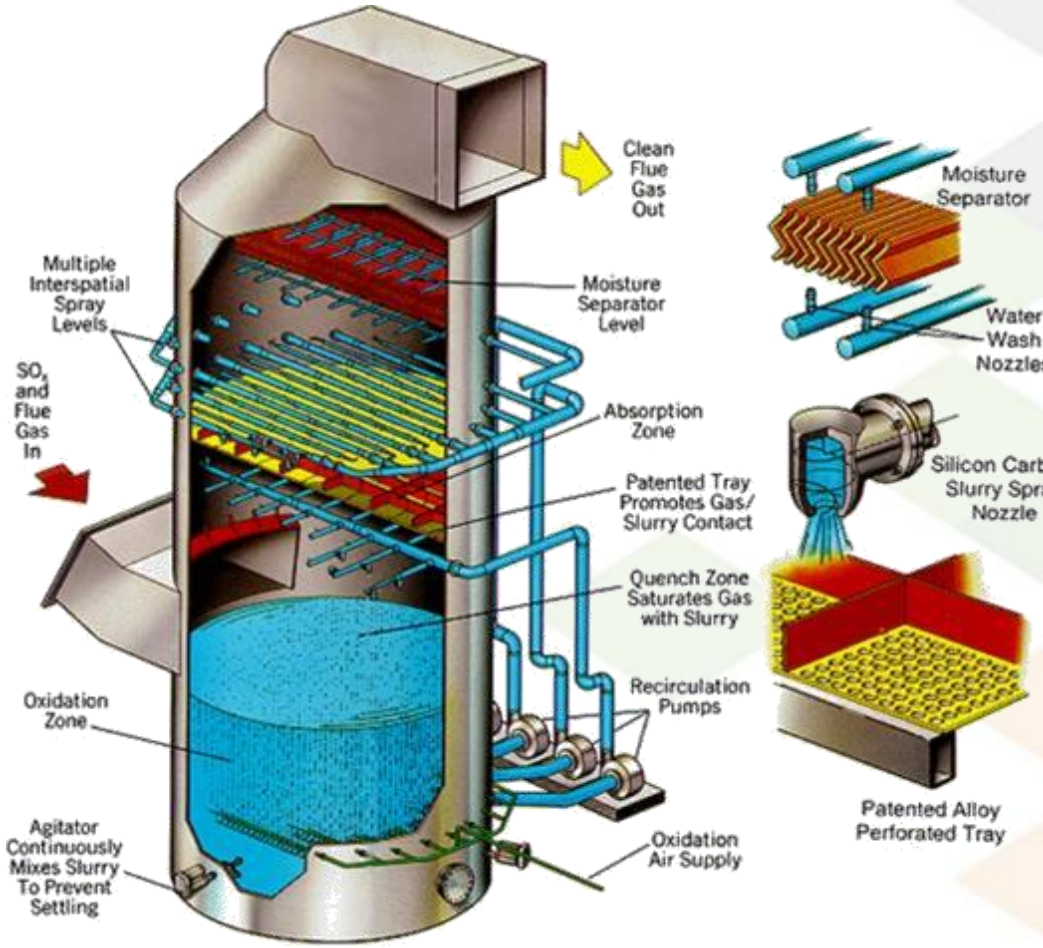


Semi-Dry Absorber

- Slurry sprayed directly onto exhaust gas



Chapter 5: Absorption Controls



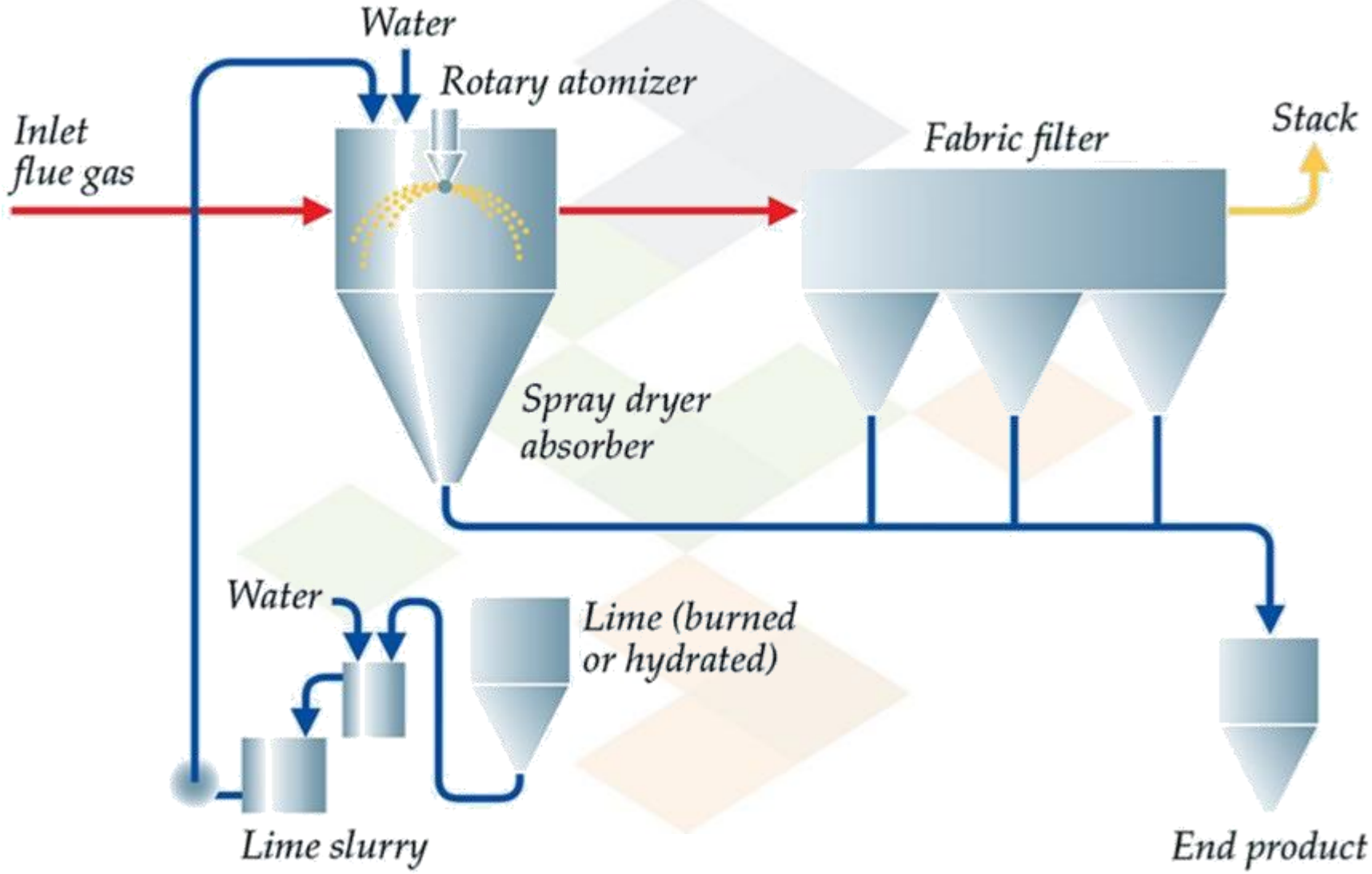
Wet Flue Gas Desulfurization (FGD)

- Moisture Separator: Prevents slurry from exhausting
- Tank Agitator: Keeps solids in suspension
- Absorption: SO_2 absorbed in slurry of alkaline reagent
- Quench: Saturates and cools flue (exhaust) gas

Semi-Dry Scrubbers for Acid Gases

- Inject an alkaline slurry into an absorber chamber
  - Add alkaline (base) into a minimal amount of water
    - Limestone: Calcium Carbonate – $CaCO_3$
    - Slaked / Hydrated Lime: Calcium Hydroxide – $Ca(OH)_2$
    - Sodium Hydroxide - NaOH
  - Acid gases react with alkaline reagent to form solid salts
  - High temperature of exhaust gas evaporates water from slurry
  - Solids (PM) capture like a baghouse or electrostatic precipitator to collect salts

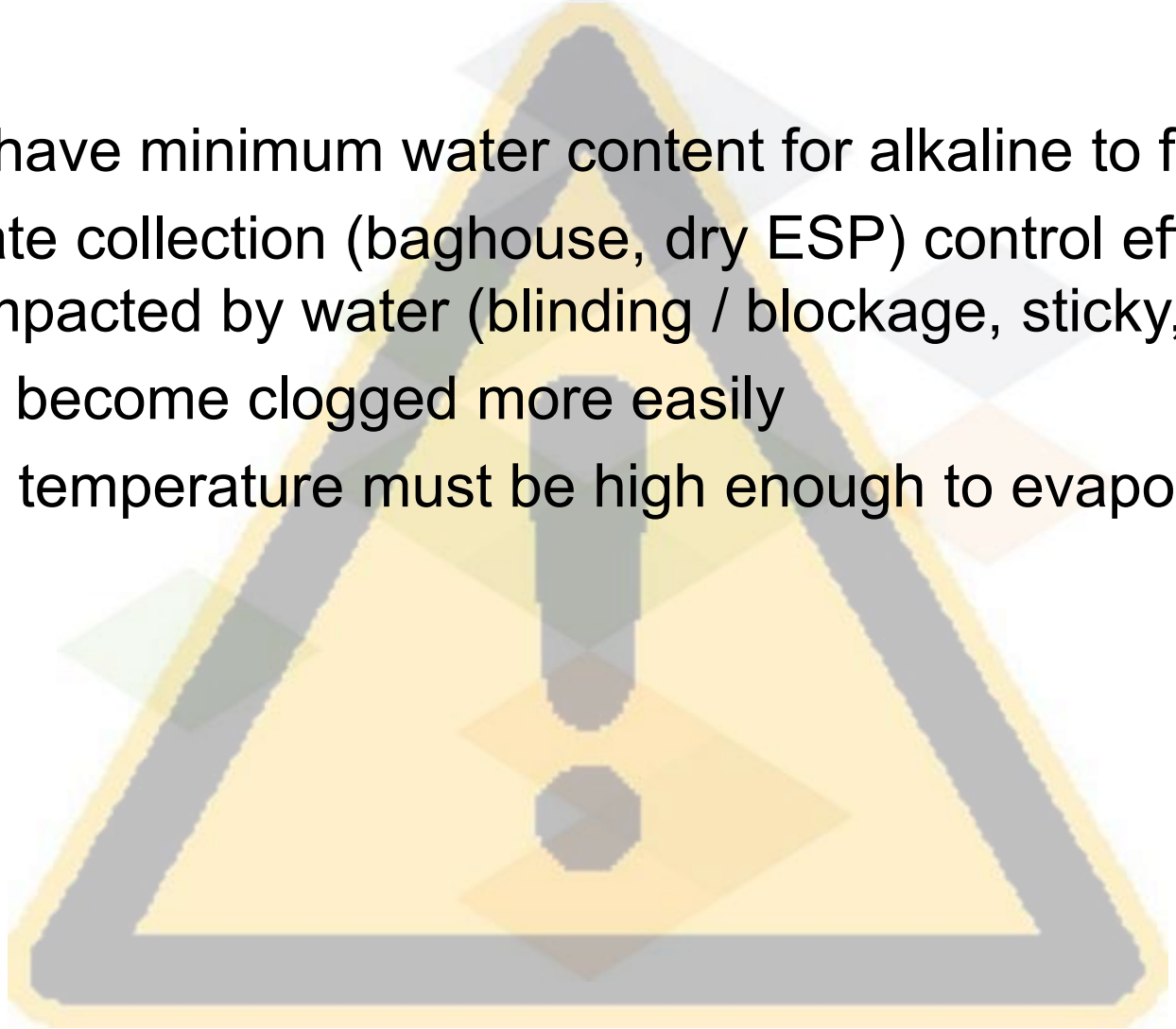
Chapter 5: Absorption Controls



Chapter 5: Absorption
Video

5.0 - Absorption Spray Dryer.mp4

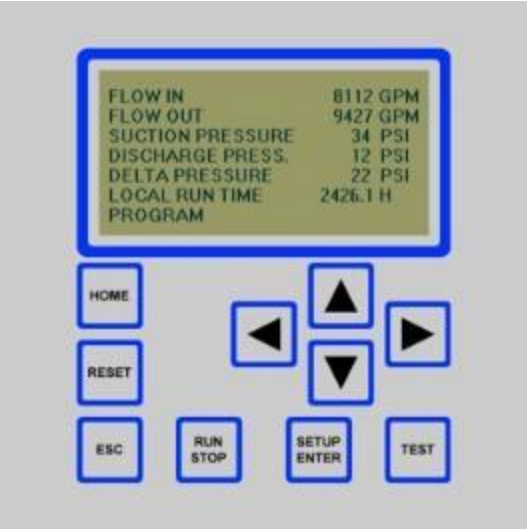
- **Semi-Dry**
  - Slurry must have minimum water content for alkaline to flow from nozzle
  - Dry particulate collection (baghouse, dry ESP) control efficiency is negatively impacted by water (blinding / blockage, sticky, mold)
  - Nozzles can become clogged more easily
  - Exhaust gas temperature must be high enough to evaporate water



Parametric Monitoring

1. Scrubber Liquid Flowrate
2. pH
3. Temperature
4. Pressure Differential (ΔP)



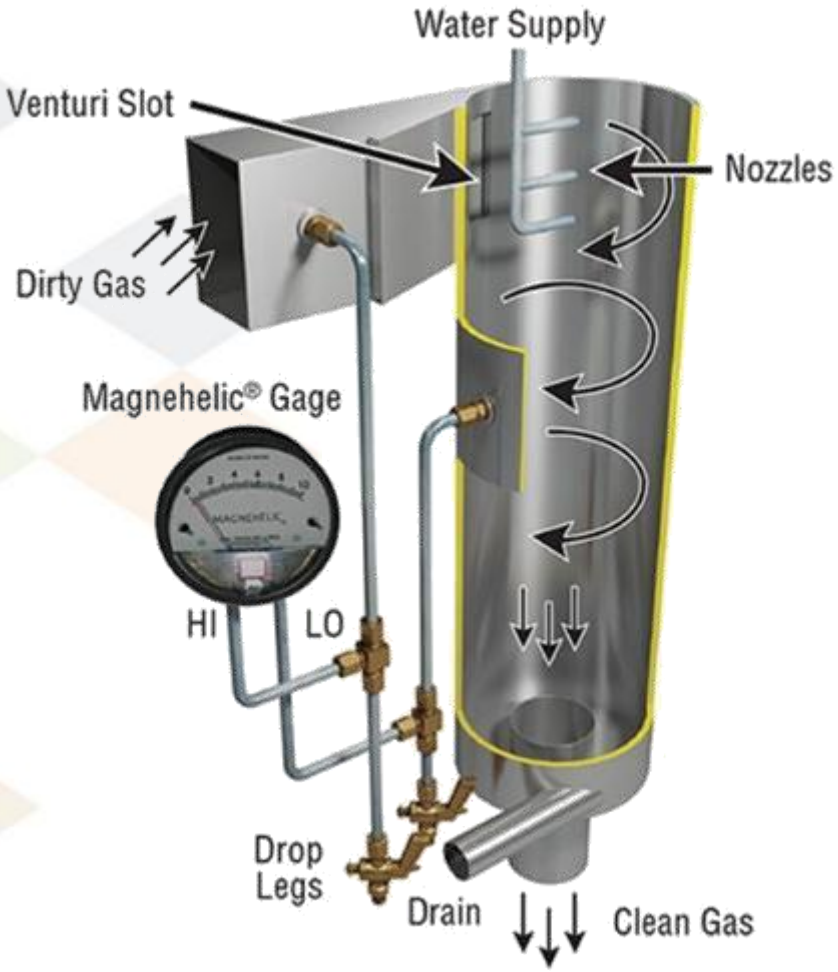




Magnehelic Gauge

- Measures differential pressure (drop) across scrubber
- Higher differential pressure, better solvent / air contact





Scrubber Liquid Flow Rate

- Scrubber liquid inlet and outlet flowrates monitored in gallons per minute
  - If outlet is significantly less than inlet, where is liquid going (leaking, flooding)?

Scrubber Liquid Parameters

- Scrubber liquid must be treated if recirculated
  - Solids removal (sampling)
  - pH adjustment (sampling or inline sensor)
  - Alkaline addition
  - Solvent concentration (if not using water)



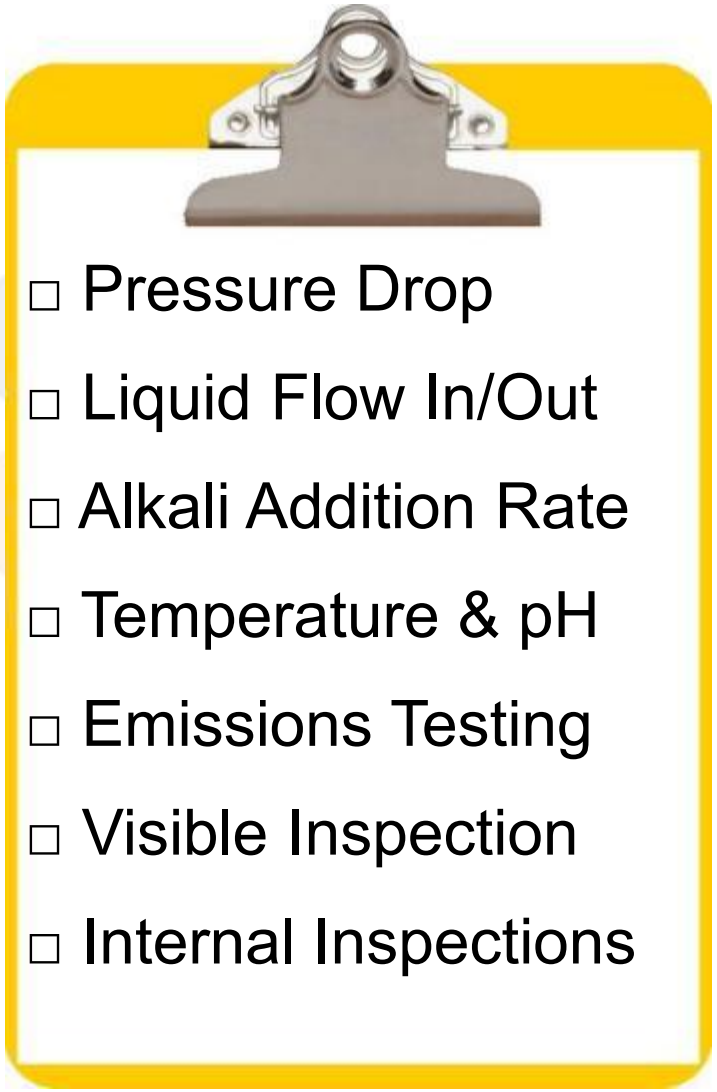


- **CEMS**
  - CEMS/Continuous Opacity Monitoring Systems (COMS) generally cannot be used on wet scrubbers because the presence of high concentrations of water (or other scrubber liquid) creates erroneous readings
  - Requires specialized instrumentation and gas treatment for water removal



Inspection Parameters

- Pressure differential
  - Wet scrubber **AND**
  - Mist eliminator
- Scrubber liquid flow/alkaline addition rate
- Inlet and outlet temperatures
- Liquid parameters (pH)
- Corrosion, rust, leaking, and droplet re-entrainment
- Internal inspection report

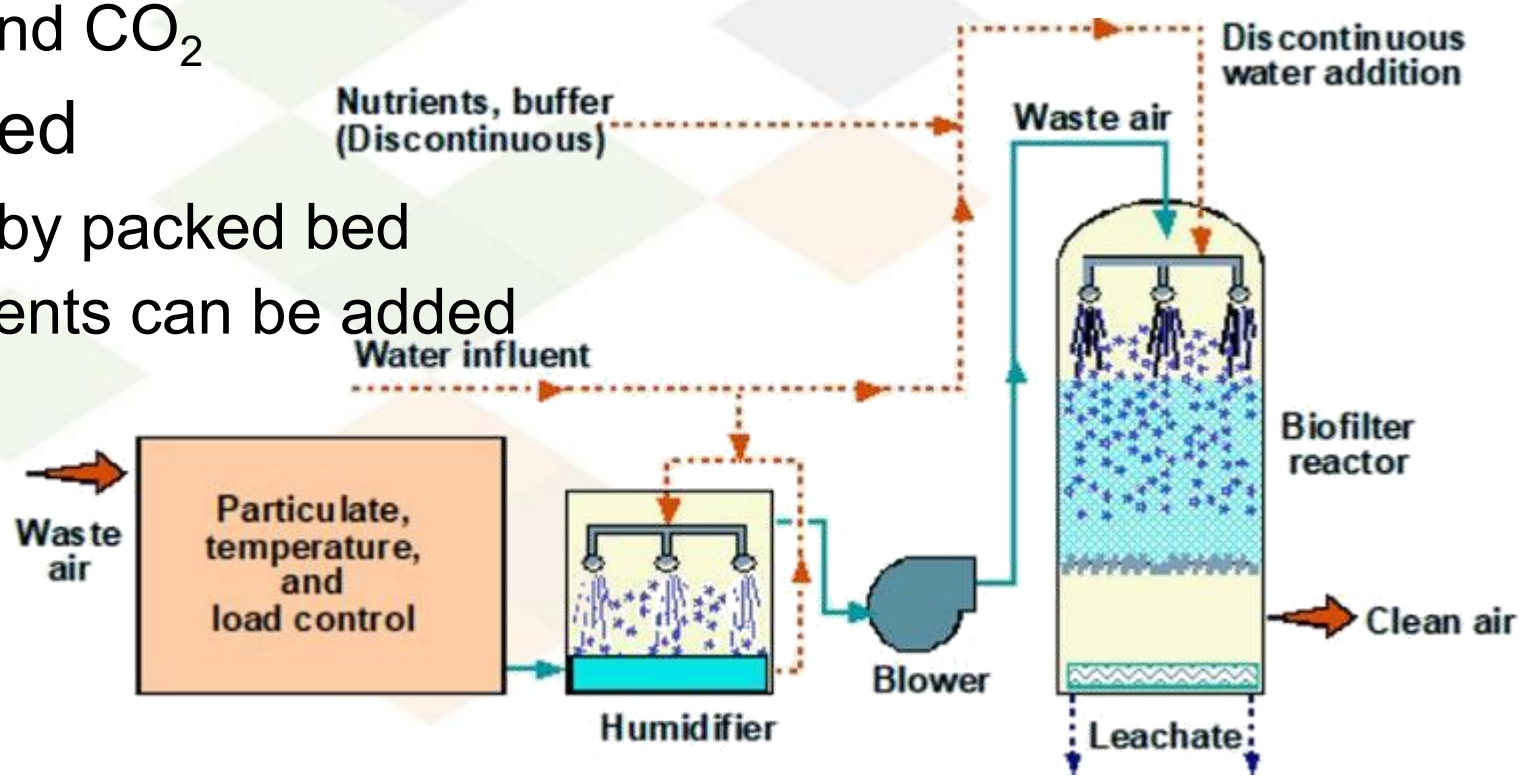


Biological Treatment (Bioreactors)

- Microorganisms are used to breakdown (convert) gaseous air pollutants into less harmful end products
  1. Biofilters: Air passes through an organic packed bed of biofilm
  2. Biotrickling Filters: Air passes through an inorganic packed bed of biofilm that is fed with a nutrient solution
  3. Bioscrubbers: Absorption wet scrubber to transfer gaseous pollutants to liquid, then a bioreactor for breaking down the liquid contaminants
- Exhaust air must be pre-treated
  - Remove compounds toxic to microbes and adjust temperature / pH
- Pollutants must be biodegradable (PM, H_2S, VOC, and CH_4)

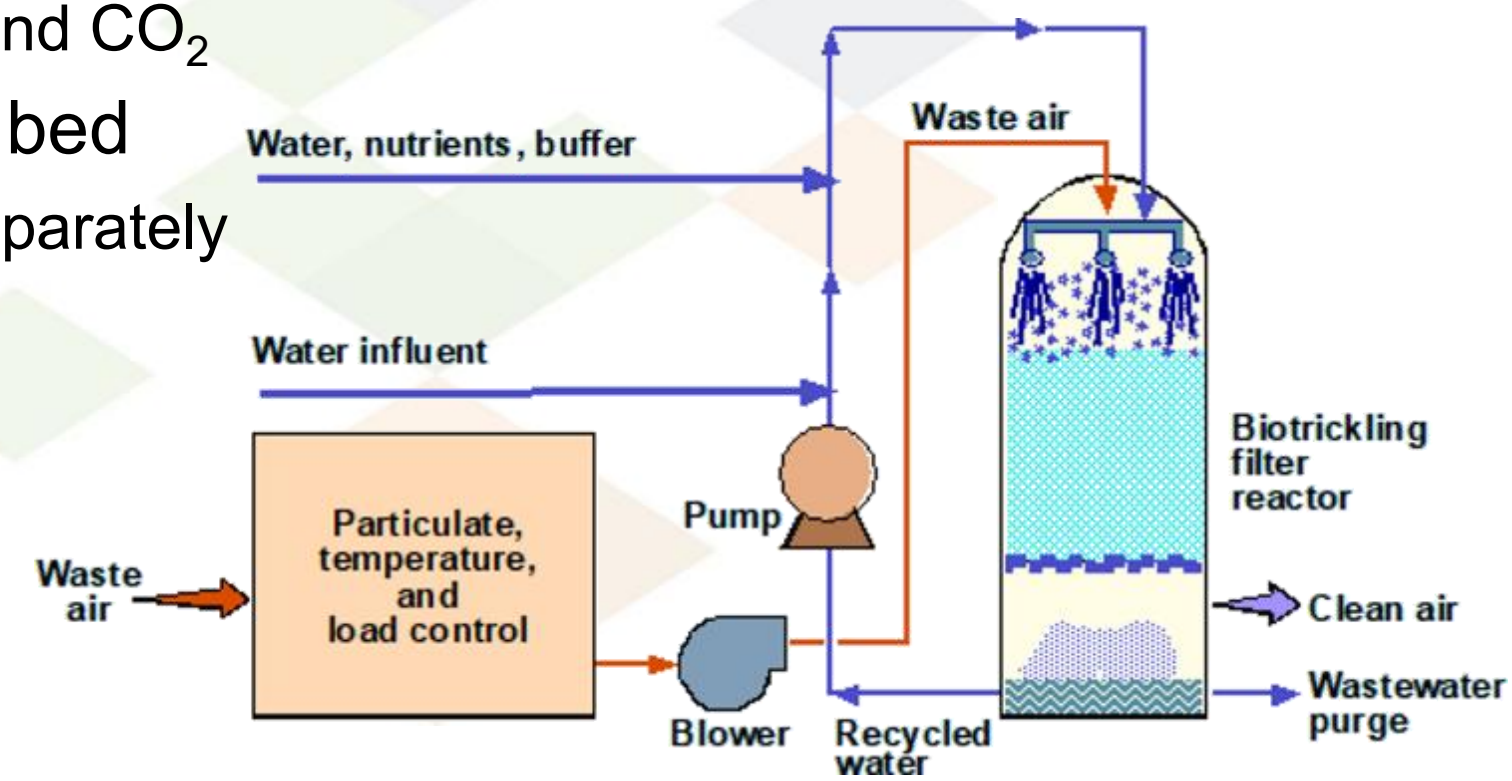
Biofilter (1 Step)

- Pollutant absorption by microbes occurs in biofilter reactor
  - Gaseous pollutants are absorbed (and decomposed) by microbes, resulting in water and CO_2
- Organic packed bed
  - Nutrients provided by packed bed
  - Supplemental nutrients can be added



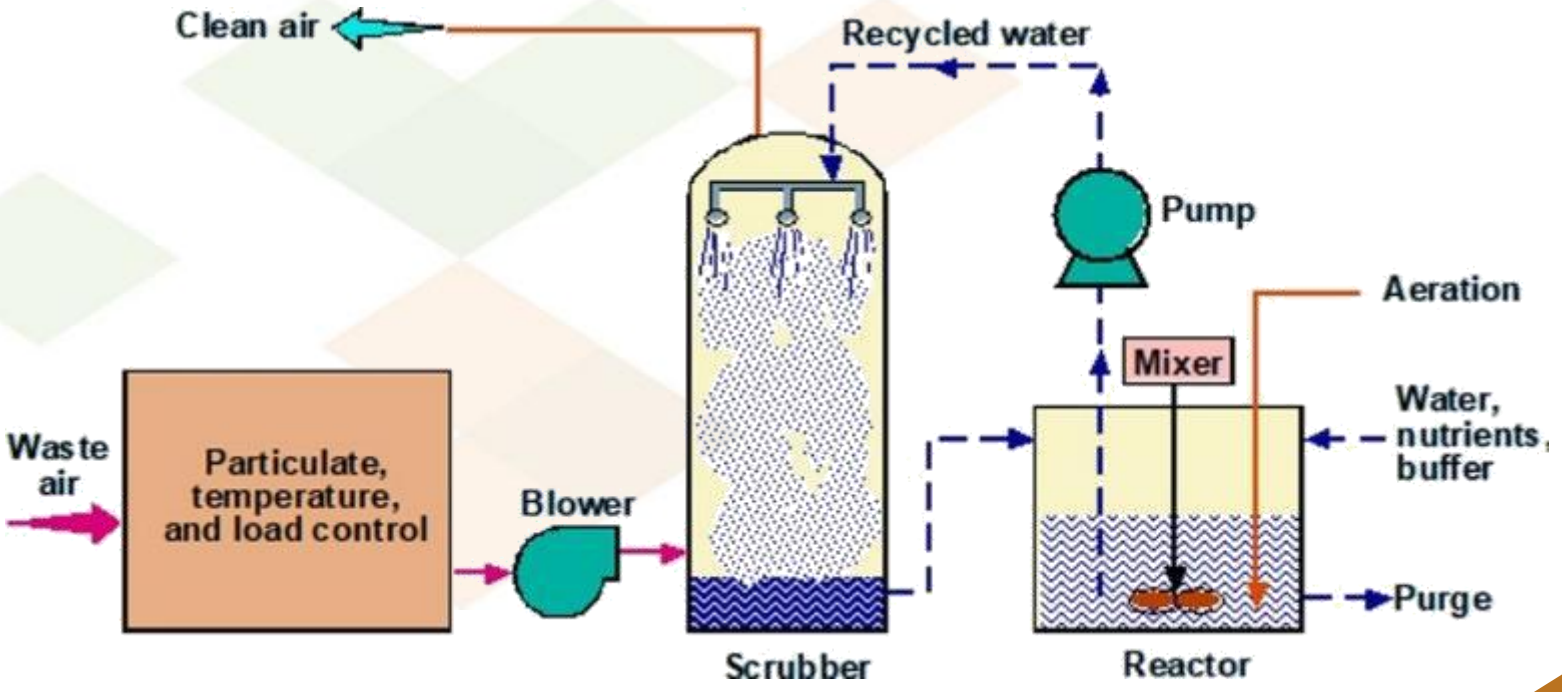
Biotrickling Filter (1 Step)

- Pollutant absorption by microbes occurs in biotrickling filter
  - Gaseous pollutants are absorbed (and decomposed) by microbes, resulting in water and CO_2
- Inorganic packed bed
  - Nutrients added separately



Bioscrubber (2 Step)

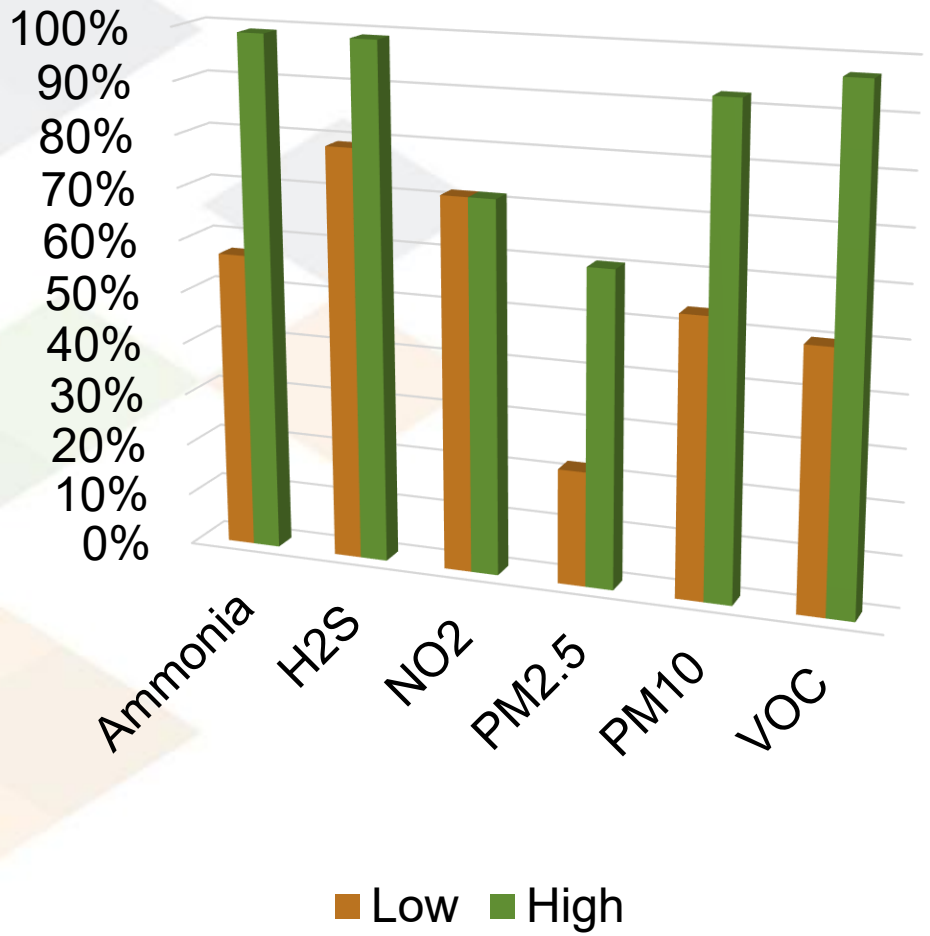
1. Pollutant absorbed in scrubber
2. Wet scrubber liquid waste is treated in bioreactor, resulting in water and CO_2



Control Efficiency

- Highly dependent on microbial health
- VOC must be dissolvable in water
  - Some VOC controlled better than others

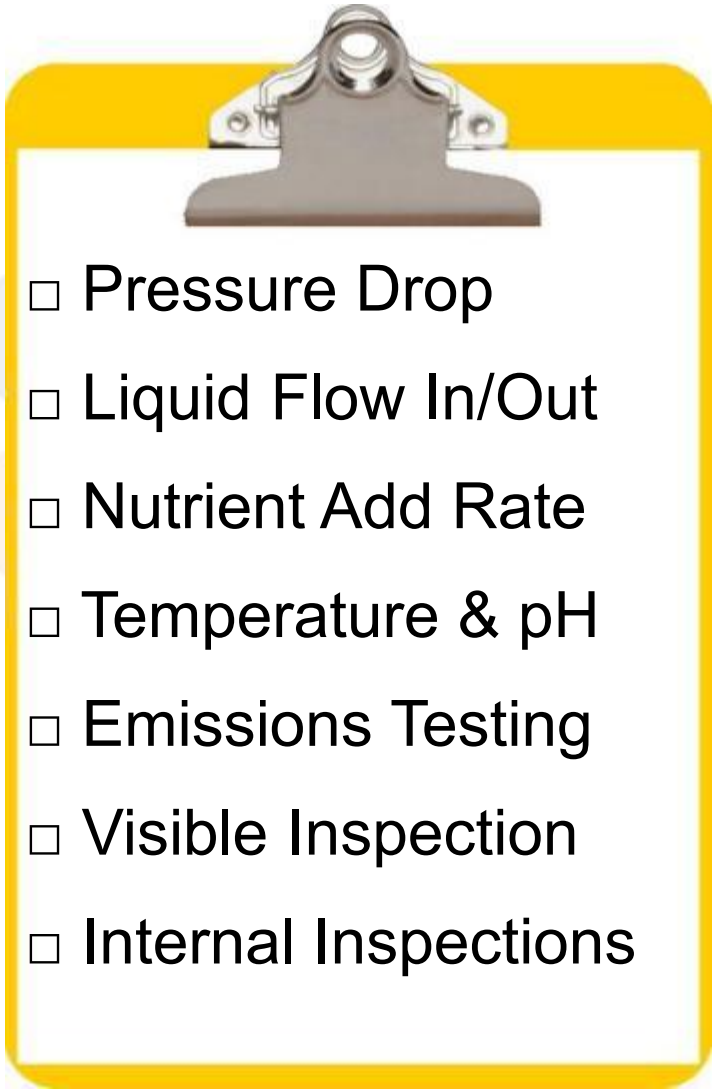
From: Air Pollutants Removal Using Biofiltration Technique: A Challenge at the Frontiers of Sustainable Environment (10/19/2022) doi: 10.1021/acsengineeringau.2c00020



- **Biological Treatment Operating Problems**
  - **Biomass Clogging:** Excess microbial growth reduces airflow
  - **Moisture:** Reactor microbes must not dry out or be too wet
  - **Solubility:** VOC must dissolve in water for access to microbes
  - **Nutrients:** Nutrients support microbial decomposition of VOC
  - **pH:** Too acidic or basic environment will kill microbes
  - **Temperature:** Temperature extremes (generally <68ºF or >105ºF) will kill microbes
  - **Degradation:** Organic packed beds degrade over time
  - **Concentration:** Too high VOC concentration will kill microbes
- **And all of the problems of a packed bed tower**

Inspection Parameters

- Pressure differential
- Nutrient / water addition rate
- Reactor temperature
- Outlet pH
- Corrosion, rust, leaking, and droplet re-entrainment
- Internal inspection report



Chapter 5: Absorption
Recap

In this chapter, we discussed:

- How absorption control technologies operate
- Common types of absorption control technologies
- Key design considerations for absorption control technologies
- Typical achievable control efficiencies
- Monitoring methods for absorption control technologies
- Common problems with absorption control technologies
- Ensuring compliance