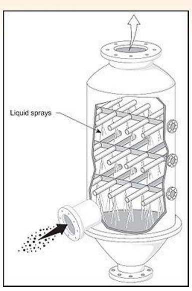
EVE 402
Air Pollution Generation and Control

Chapter #5 Lectures (Part 5)

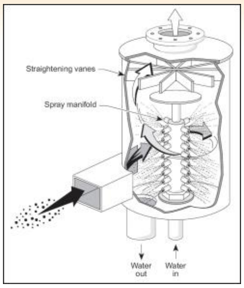
Wet Collectors

- Water is used to either capture particulate or increase aerosol size
  - *Hygroscopic* particles (those that attract and hold water molecules) "grow"
  - Optimum water droplet diameter: 50 – 1000 μm
- Same collection mechanisms
  - Inertia (assumed dominant mode in models)
  - Interception
  - Diffusion (Brownian motion)

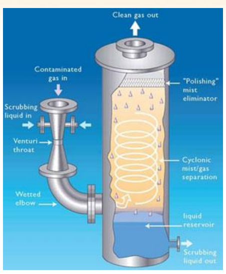
Type 1: Spray Chamber Scrubber



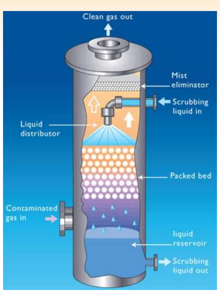
Type 2: Cyclonic Scrubber



Type 3: Venturi Scrubber



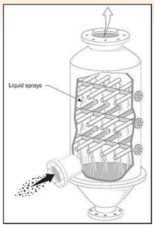
Type 4: Packed Tower



Used primarily for gas adsorption, which we'll get to in Chapter 6

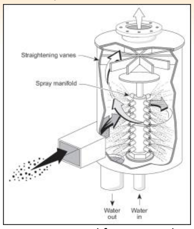
Recap

Spray Chamber Scrubber



- Counter-current flow
- Droplets capture particles and fall to bottom
- Efficiency increases as V_g decreases
- ΔP: 250 Pa

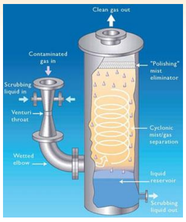
Cyclonic Scrubber



- Water sprayed from central manifold captures particles; forced to walls
- Clean air travels upward through straightening vanes (decr. turbulence)
- ΔP: 250 - 2500 Pa

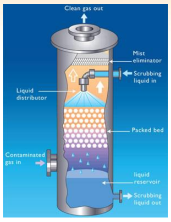
Recap (2)

Venturi Scrubber



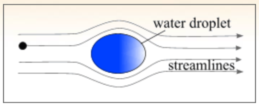
- Gas velocity increases in throat
- High velocity atomizes liquid and produces "targets"
- More efficient than cyclone scrubbers
- ΔP: 5 – 15 kPa

Packed Tower



- Layers of variously-shaped packing materials (large surface area)
- Water coats packing and adsorbs particles

A Simple Model



If stopping distance (x_s) exceeds the original distance from the point where it left the streamline, impaction will occur.

- A particle approaches a droplet and undergoes inertial impaction
- At some point, it leaves the streamline
- Two forces on particle: inertia and drag
- Particle eventually stops (relative to droplet)

A Simple Model (2)

- Impaction of particles onto a collector body is characterized by the dimensionless **impaction number (N_I) also known as Stokes number (S_{tk})**
- S_{tk} is a ratio of the particle's stopping distance (x_s) to a characteristic length of the collector body (e.g., diameter of the water droplet, d_D)

A Simple Model (3)

$$S_{tk} = N_I = \frac{x_s}{d_D} = \frac{\tau V_{po}}{d_D}$$

where,

N_I = Impaction Number = S_{tk} = Stokes Number
x_s = stopping distance
τ = relaxation time
V_{po} = initial velocity of the particle relative to the droplet
d_D = droplet diameter

The **relaxation time (τ)** can be determined by applying a **force balance** on a particle that is decelerating in the horizontal direction

The stopping distance (x_s) needs to be determined to calculate S_{tk}. Newton's 2nd law can be used to describe a decelerating particle of constant mass moving in the horizontal direction and assuming Stokes law

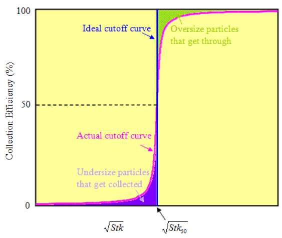
$$F_{inertial} + F_{drag} = 0$$

$$\frac{m_p dV_p}{dt} = -\frac{3\pi\mu_g d_p V_p}{K_c}$$

See pages 233 – 236 in your text

Particle collection efficiency versus Stokes Number

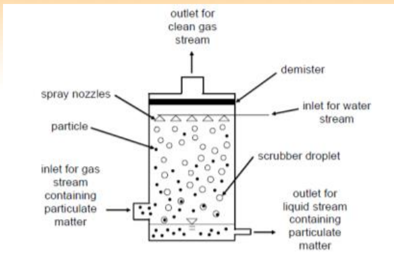
See Figure 5-18, pg. 235



In an ideal situation, an impactor has a "sharp cutoff", i.e., all particles greater than a certain size are collected while all particles smaller than that size pass through. This size is called the ***cutoff size***

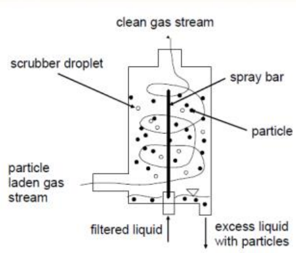
$$S_{tk} = N_I = \frac{d_p{}^2 \rho_p K_c V_{po}}{18 \mu d_D}$$

Wet Collector Types: More Detail



- **Spray chamber scrubber**– typically operates with liquid collector bodies (scrubber droplets) traveling downward and the gas stream containing the particulate contaminant material traveling upward.

Cyclonic scrubbers, or wet cyclones, produce droplets of water with a spray bar that is located along the centerline of the cyclone. These droplets then collect particulate matter as they are transported to the outer edge of the cyclone. The liquid also allows cleansing of the walls of the cyclone.

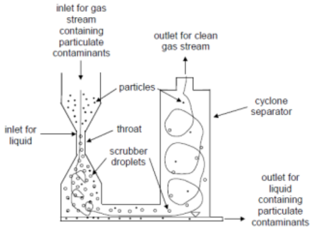


Venturi scrubbers work by accelerating the gas stream to velocities around 50 to 150 m/s. The gas stream accelerates because the duct that contains the gas stream is constricted.

At throat
1. Velocity increases
2. Static pressure decreases

$A_{inlet} : A_{throat} = 4:1$

Venturi Scrubber and Cyclone Separator



- Equations are developed in Air Pollution: *Its Origin and Control* that describe the particle removal efficiency that can be achieved by a venturi scrubber and the pressure drop that results from atomizing the scrubber droplets and accelerating the droplets to approach the same velocity as the gas streams.

Assumptions used in the development of the venturi scrubber model include:

- Gas velocity is constant throughout the length of the venturi's throat
- Flow is one dimensional, incompressible, and adiabatic
- Atomized droplets collect the particles by impaction
- Droplets are uniformly distributed along the cross section of the venturi's throat
- Diameter of the scrubber droplets remain constant
- Volume ratio of the scrubber droplets to the gas stream is small
- Pressure forces around the scrubber droplets are symmetrical and therefore ignored

By considering a force balance on the atomized droplets, an equation can be developed that describes how the scrubber droplets accelerate along the length of the venturi's throat and the pressure drop caused by accelerating the droplets. Such a force balance results in the following equation for pressure drop:

$$\Delta P = \beta \rho_L u_g^2 \left(\frac{Q_L}{Q_G} \right)$$

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Where,

ΔP = -change in pressure across the length of the venturi's throat (-($P_2 - P_1$)) = pressure drop

β = correction factor for droplets lost to walls of venturi = 0.85

u_g = velocity of gas in the venturi's throat

$\left(\frac{Q_L}{Q_G} \right)$ = volume ratio of liquid to gas flow rates

$$\Delta P = \left[\text{cm } H_2O_{(l)} \right]$$

$$\beta = [-]$$

$$u_g = \left[\text{cm}/\text{s} \right]$$

$$\frac{Q_L}{Q_G} = [-]$$

Calvert Equation (mixture of theory and experimental results)

$$\Delta P = 1.03 \times 10^{-3} u_G^2 \left(\frac{Q_L}{Q_G} \right)$$

ΔP = pressure drop [cm H_2O]

u_G = velocity of gas at the throat [cm/s]

$$\frac{Q_L}{Q_G} = [-]$$

Equation 5-83, page 244

Hesketh (developed from experimental data)

$$\Delta P = \frac{V_{g,t}^2\ \rho_g\,(A)^{0.133}}{507}\left(0.56 + 0.125L + 2.3\times10^{-3}L^2\right)$$

$\Delta P =$ pressure drop across the venturi [in H_2O]

$V_{g,t} =$ gas velocity at the throat [ft/s]

$\rho_g =$ gas density downstream from the venturi throat [lb/ft^3]

$A =$ cross-sectional area of the venturi throat [ft^2]

$L =$ liquid to gas ratio $\left[\dfrac{\text{gal}}{1000\text{ actual ft}^3}\right]$

Particle collection **efficiency** achieved by a venturi scrubber has been described by considering the removal of particles due to **impaction, pressure drop, contaminant particle diameter, viscosity of the gas stream, and densities of the scrubber liquid** droplets and contaminant particles as in the next slide.

Venturi Collection Efficiency

$$\eta_p = 1 - \exp\left(\frac{-\left(6.3\times10^{-4}\right)\rho_L\rho_p K_c d_p^2 u_g^2 \left(\dfrac{Q_L}{Q_G}\right) f^2}{\mu_g^2}\right)$$

where,

η_p = graded particle collection efficiency [-]

ρ_L = density of scrubber droplets

ρ_p = density of particulate contaminant

K_c = Cunningham correction factor for particulate contaminant [-]

d_p = diameter of particulate contaminant

u_g = gas velocity at throat

f = experimental coefficient = 0.1 to 0.4 [-]

μ_g = gas viscosity

Use any set of dimensionally consistent units

Characteristics of Wet Scrubbers

Advantages	Disadvantages
Possible to achieve high particle collection efficiency	Requires the use of a liquid medium that needs to be treated
Humidifies and cools gas stream	High pressure drop for high particle collection efficiencies
Possible to simultaneously remove particles and gases (even sticky particles)	Corrosion and precipitation can occur
Variable throat area of venturi allows selection of particle collection efficiency	Liquid can freeze

Typical Values for Venturi Scrubbers

$$50\frac{m}{s} < u_g < 100\frac{m}{s}$$

$$0.2\frac{L}{m^3} < \frac{Q_L}{Q_g} < 2.0\frac{L}{m^3}$$

$$5-10\%\left(d_p \sim 0.1\mu m\right) < \eta_d < 100\%\left(d_p \sim 50\mu m\right)$$

$$10 \text{ cm } H_2O_{(l)} < \Delta P < 70 \text{ cm } H_2O_{(l)}$$

Recap: Venturi Relationships

$$\Delta P = \beta \rho_L u_g^2 \left(\frac{Q_L}{Q_G}\right)$$

$$\Delta P = 1.03 \times 10^{-3} u_g^2 \left(\frac{Q_L}{Q_G}\right)$$

$$\Delta P = \frac{V_{g,t}^2 \rho_g A^{0.133}}{507}(0.56 + 0.125L + 2.3 \times 10^{-3} L^2)$$

$$\eta_p = 1 - \exp\left(\frac{-\left(6.3\times10^{-4}\right)\rho_L \rho_p K_c d_p^2 u_g^2 \left(\frac{Q_L}{Q_G}\right) f^2}{\mu_g^2}\right)$$