7 Particulate Scrubbers

7.1 Collection Mechanisms

Introduction

Wet collection devices for fumes, mists, and suspended dusts are called scrubbers. This class of pollution control equipment collects particles by direct contact with a liquid (usually water). There are a multitude of scrubber designs on the market; most of them can be grouped according to the liquid contacting mechanism used. In addition, scrubbers can be broadly classified as low-, moderate-, or high-energy units. Energy requirements can be expressed as the pressure drop across the scrubber. In this chapter, we will briefly describe the most frequently used scrubber designs, and will also discuss some typical operating conditions.

Spray-Chamber Scrubbers

In spray-chamber scrubbers, particulate-laden air is passed through a circular or rectangular chamber and contacted with a liquid spray produced by spray nozzles. The nozzles are arranged in a pattern(an array of spray nozzles) that completely covers the gas flow path. Nozzles providing a cone spray geometry are the most effective. Droplet size is controlled to optimize particle contact and to provide easy droplet separation from the airstream. Figure 5.1 shows spray chamber arrangements employing countercurrent and cross-flow contact between gas and liquid. Baffles are sometimes used to improve gas-spray contact. Recirculated water must be sufficiently settled or filtered to prevent excessive nozzle fouling. Nozzle cleaning and replacement represent a major part of the required maintenance for spray chambers.

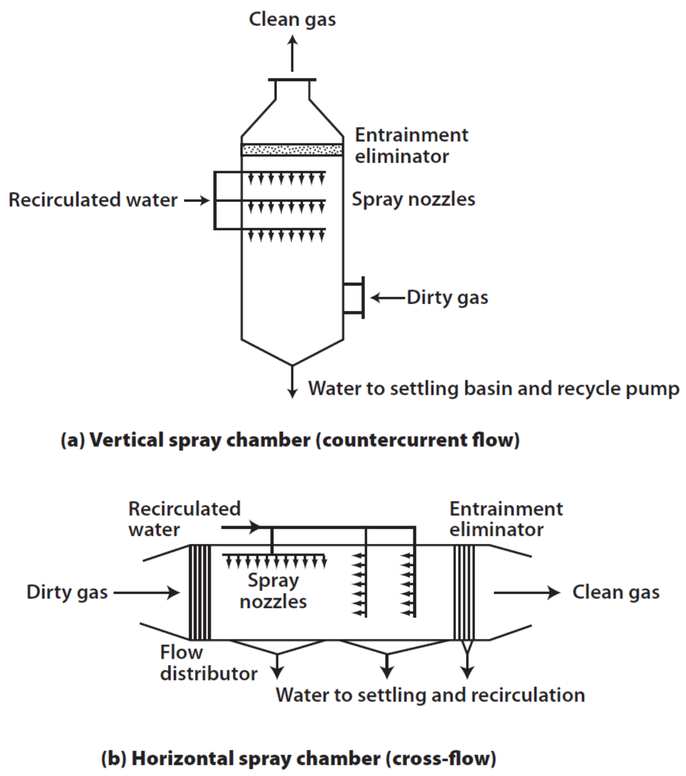


Figure 7.1 Typical spray chamber arrangements.

Spray scrubbers(all particulate wet scrubbers) use the same basic collection mechanisms — interial impaction and Brownian motion. Use a three-step process:

- Particle capture in either droplets, liquid sheets, or liquid jets
- Capture of the liquid droplets entrained in the gas stream
- Removal and treatment of the particulate matter-contaminated liquid prior to discharge

When the dusty gas approaches the droplet, the air flow will bypass the droplet, and the dust particles with larger particles (usually dp>1um), due to the inertia, continue to maintain the original direction of motion, impact on the droplet and become trapped.

For a single spherical droplet, under potential flow conditions, its inertial trapping efficiency is:

$$\eta_I = \left(\frac{s_{tk}}{s_{tk}+0.35}\right)^2 \qquad (7.1)$$

$$s_{tk} = \frac{C\rho_p d_p^2 V_r}{18\mu_g D} \qquad (7.2)$$

where: η_I= the dust collection efficiency of a single droplet due to inertial collision; C=Cunningham correction coefficient; ρ_p =the density of particulate matter， kg/m^3; d_p = the particle size, m; V_r is the relative velocity between particle and droplet, Vd-Vp, and Vd and Vp are the final settling velocity of droplet and particle, respectively; μ_g is the viscosity of a gas, $Pa{\cdot}s$; D is the diameter of the droplet, m.

Venturi Scrubbers

Venturi dust collector is an efficient wet dust collector. Its structure is shown in Figure 2, which is mainly composed of four parts: gradual pipe, throat, gradual expansion pipe and dehydrator. After the exhaust gas enters the shrinking pipe, due to the decreasing cross-sectional area, the air velocity gradually increases. When it reaches the throat, the flow velocity reaches the maximum, which is usually 5 to 12 times of the flow velocity at the entrance of the shrinking pipe. The water droplets sprayed from near the throat are affected by the air flow at such a high speed into smaller droplets. The gas film on the surface of the dust particles is broken, and the dust particles are moistened by water.

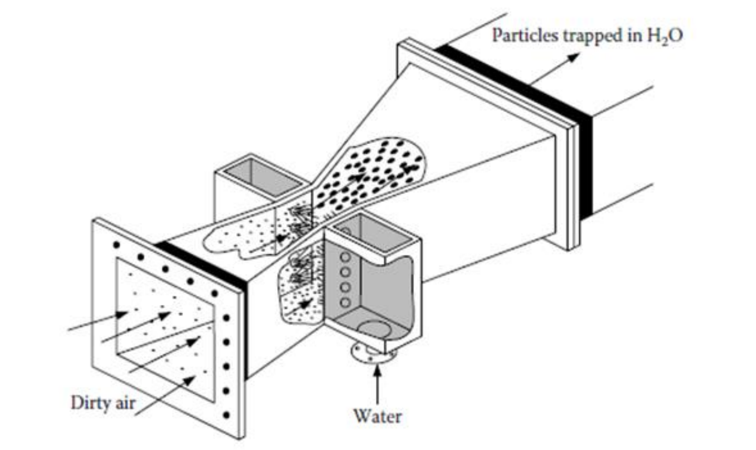


Figure 7.2 Typical Venturi structure

At the same time, due to the rapid increase of dynamic pressure and decrease of static pressure in the throat, the water droplets evaporate rapidly, so that the water vapor in the gas reaches a saturated or even super-saturated state. In the expanding tube, the airflow speed decreases, the static pressure rises, the supersaturated water vapor begins to condense, and the fine dust particles become condensation nuclei. In this way, regardless of the particle size in the flue gas, its surface will be attached to a layer of water film, the dust particles attached to the water film and water droplets or other particles collide with each other, becoming a larger polymer. They are then collected in a dehydrator.

7.2 Collection Efficienc

Spray-Chamber Scrubbers

The dust removal efficiency of spray tower is closely related to dust particle size, droplet diameter and liquid-gas ratio. Assumptions: (1) from the nozzle of the droplet size, same diameter is D, the terminal settling velocity for V_d; The absolute decline speed relative to of the tower wall (real descent velocity) $u_D = V_d - V_g$ (V_g for the rising velocity of the gas, superficial gas velocity); (2) The droplet distribution is uniform on the cross section of the tower; (3) The droplets do not affect each other; ④ The absolute upward velocity (true upward velocity) of Grade i particulate matter is $u_p = V_g - V_p$(V_p is the final settling velocity of Grade i particulate matter, relative to the airflow). Because of particles and droplets reverse movement, so the particles relative to the droplet velocity : $u_p + u_D = V_d - V_p$.

Calvert (1977) developed the following equation for particle collection in a countercurrent vertical spray chamber.

$$\eta_i = 1 - \mathrm{Pt}_i = 1 - exp(-\frac{3}{2}\frac{Q_l}{Q_g}\cdot\frac{H}{D}\cdot\frac{V_d - V_p}{V_d - V_g}\cdot\eta_{Ti}) \qquad (7.3)$$

where

η_i =collection efficiency of a given particle size i; Pt_i = penetration of a given particle size i ; Q_l = volumetric liquid flow rate, m^3/s;Q_g = volumetric gas flow rate, m^3/s;V_g = superficial gas velocity, m/s;V_d = terminal settling velocity of droplets, m/s; V_p = terminal settling velocity of particle, m/s ; η_{Ti} = fractional collection efficiency of a single droplet;D = droplet diameter, m;H = leight of scrubber contact zone, m.

The single droplet target efficiency is estimated from

$$\eta_{Ti} = (\frac{stk_i}{stk_i+0.7})^2 \qquad (7.4)$$

$$stk_i = \frac{C\rho_p d_{pi}^2(V_d - V_p)}{9\mu_g D} \approx \frac{\rho_p d_{pi}^2 V_d}{9\mu_g D} \qquad (7.5)$$

where

C = Cunningham correction factor, dimensionless; ρ_p = particle density, kg/m^3; d_{pi} = physical particle diameter, m; μ_G = gas viscosity, Pa·s.

For cross-flow chambers, Eq. (7.3) can be modified to

$$\eta_i = 1 - \mathrm{Pt}_i = exp(-\frac{3}{2}\frac{Q_l}{Q_g}\frac{H}{D}\cdot\eta_{Ti}) \quad (7.6)$$

Example 7.1

Calculate the collection efficiency of an 8 μm density-1000 kg/m^3 particle through a vertical countercurrent spray chamber if the operating conditions are $Q_L/Q_G = 1$ L/m^3, $V_g = 20$ cm/s, $D = 300\mu$m and H= 3 m. Assume atmospheric standard pressure and 25°C.

Solution

For this problem, we use Eqs. (7.3), (7.4), and (7.5). From Table B. 2 in Appendix B, $\mu_g = 0.044\ \mathrm{lb_m/hr \cdot ft} = 1.8 \times 10^{-5} P_a \cdot s$, $\rho_{air} = 1.185$ kg/m^3.

the settling velocity of an 8μm particle(Assuming Stokes regime flow)

$$V_p = \frac{\rho_p d_{pi}^2}{18\mu} g = \frac{1000 \times (8 \times 10^{-6})^2}{18 \times 1.8 \times 10^{-5}} \times 9.81 = 1.94 \times 10^{-3}\, m/s$$

the settling velocity of an 300μm droplets(Assuming Transition regime flow) ,

$$V_d = \frac{0.153 d_p^{1.14} \rho_p^{0.71} \mathrm{g}^{0.71}}{\mu^{0.43} \rho^{0.29}} = \frac{0.153 \times (300 \times 10^{-6})^{1.14} \times (1000 \times 9.81)^{0.71}}{(1.8 \times 10^{-5})^{0.43} \times 1.185^{0.29}} = 1.05\, m/s$$

Check $Re_P = \frac{300 \times 10^{-6} \times 1.185 \times 1.05}{1.8 \times 10^{-5}} = 20.79$ $2 \leq Re_P \leq 500$ **OK**

$$stk_i = \frac{C \rho_p d_{pi}^2 (V_d - V_p)}{9 \mu_g D} \approx \frac{\rho_p d_{pi}^2 V_d}{9 \mu_g D} = \frac{1000 \times (8 \times 10^{-6})^2 \times 1.05}{9 \times 1.8 \times 10^{-5} \times 300 \times 10^{-6}} = 1.38$$

$$\eta_{Ti} = (\frac{stk_i}{stk_i + 0.35})^2 = \left(\frac{1.38}{1.38 + 0.7}\right)^2 = 0.44$$

$$\eta_i = 1 - \mathrm{Pt}_i = 1 - exp(-\frac{3}{2} \frac{Q_l}{Q_g} \cdot \frac{H}{D} \cdot \frac{V_d - V_p}{V_d - V_g} \cdot \eta_{Ti}) = 1 - \exp(-\frac{3}{2} \times 0.001 \times \frac{3}{300 \times 10^{-6}} \times \frac{1.05}{1.05 - 0.2} \times 0.44) = 0.9997$$

Venturi Scrubbers

Particle penetration through a venturi scrubber can be approximated by the following equation, developed by Calvert et al. (1972).

$$\mathrm{Pt}_i = 1 - \eta_i = \exp\left\{\frac{2}{55}\frac{Q_l}{Q_g}\frac{D\rho_l}{\mu_g}V_T\left[-0.7 - stk_i f + 1.4\ln\left(\frac{stk_i f+0.7}{0.7}\right) + \frac{0.49}{0.7+stk_i f}\right]\frac{1}{stk_i}\right\} \qquad (7.7)$$

Q_l/Q_g = liquid-to-gas ratio, $\mathrm{m^3/m^3}$; D = mean droplet diameter, m; ρ_l = density of the liquid, $\mathrm{kg/m^3}$; μ_l = liquid viscosity, $P_a \cdot s$; V_T = gas velocity in throat, m/s; f = empirical factor ($f = 0.25$ for hydrophobic particles; $f = 0.50$ for hydrophilic particles); stk_i = inertial impaction parameter $= \frac{\rho_{pi} d_{pi}^2 V_T}{9\mu_g D}$

Gas atomization produces a wide distribution of droplet size; however, Eq. (7.7) can be solved with satisfactory results using the Sauter mean droplet diameter D, which is found with the Nukiyama-Tanasawa (1938) relationship:

$$D = \frac{586\times10^3}{V_g}\left(\frac{\sigma}{\rho_l}\right)^{0.5} + 1682\left(\frac{\mu_l}{\sqrt{\sigma\rho_l}}\right)^{0.45} L^{1.5}\,(\mu m) \qquad (7.8)$$

D = Sauter mean droplet diameter, m; σ = liquid surface tension, N/m; $L = \frac{Q_l}{Q_g}$ (liquid–to–gas ratio, L/m^3).

Example 7.2

Calculate the collection efficiency of a venturi scrubber for $1\mu m$ density-1000 $\mathrm{kg/m^3}$ particles if the operating conditions are $V_g = 50$ m/s at the throat entrance, and $Q_l/Q_g = 1\ \mathrm{L/m^3}$. Assume atmospheric pressure and 20°C (at these conditions, $\sigma = 72$ dyne /cm and $\mu_L = 1$cp). Also assume $f = 0.5$ for this case.

Solution

For this problem, we use Eqs. (7.5), (7.7), and (7.8). First, we find the droplet diameter from Eq. (7.8). At 20°C, $\sigma = 7.2 \times 10^{-2}$ N/m and $\mu_L = 0.001$ Pa·s. Therefore,

$$D = \frac{586 \times 10^3}{V_g}\left(\frac{\sigma}{\rho_l}\right)^{0.5} + 1682\left(\frac{\mu_l}{\sqrt{\sigma\rho_l}}\right)^{0.45} L^{1.5} = \frac{586000}{50} \times \left(\frac{7.2 \times 10^{-2}}{1000}\right)^{0.5} + 1682\left(\frac{0.001}{\sqrt{7.2 \times 10^{-2} \times 1000}}\right)^{0.45} \times 1^{1.5}$$

$$= 99.4 + 28.7 = 128.1\mu m$$

Now we use Eq. (7.5) to obtain stk_i and then Eq. (7.8) to calculate the penetration

$$stk_i = \frac{\rho_{pi} d_{pi}^2 V_T}{9\mu_g D} = \frac{1000 \times (1 \times 10^{-6})^2 \times 50}{9 \times 1.8 \times 10^{-5} \times 128.1 \times 10^{-6}} = 2.41$$

$$F(stk_i, f) = \frac{1}{stk_i}\left[-0.7 - stk_i f + 1.4 \ln\left(\frac{stk_i f + 0.7}{0.7}\right) + \frac{0.49}{0.7 + stk_i f}\right] = -0.102$$

$$\eta_i = 1 - exp\left[\frac{2}{55}\frac{Q_l}{Q_g}\frac{D\rho_l}{\mu_g} V_T F(stk_i, f)\right] = 1 - exp\left[\frac{2}{55} \times 0.001 \times \frac{128.1 \times 10^{-6} \times 1000}{1.8 \times 10^{-5}} \times 50 \times (-0.102)\right] \approx 0.733$$

This scrubber will capture 73.3% of 1μm particles. This low efficiency is due to the low inlet velocity, which gives a low pressure drop.

7.3 Pressure Drop

Pressure Loss in Venturi Scrubbers. Pressure loss in large industrial venturi scrubbers is due primarily to droplet acceleration and can be estimated by the equation of Yung et al. (1977):

$$\Delta P = -\rho_l V_T^2 (Q_l/Q_g) u_T \tag{7.9}$$

$$u_T = 2\left[1 - X^2 + X\sqrt{X^2 - 1}\right] \tag{7.10}$$

$$X = 3L_T C_D \rho_g/(16D\rho_l) + 1 \tag{7.11}$$

where

ΔP = pressure loss,Pa;V_G = gas velocity, m/s;X = dimensionless throat length;L_T = venturi throat length, m;C_D = drag coefficient for droplets with Sauter mean diameter, dimensionless,Hesketh (1979) suggested that for droplets with Reynolds numbers in the range from 10 to 500 , the drag coefficient is given by

$$C_D = \frac{24}{\mathrm{Re}} + \frac{4}{(\mathrm{Re})^{1/3}} \tag{7.12}$$

where Re = droplet Reynolds number.

Example 7.3

Estimate the pressure drop across the venturi scrubber described in Example 7.2 if the throat length is 30 cm .

Solution

The liquid droplet Re is

$$\mathrm{Re} = \frac{DV_g\rho_g}{\mu_g} = \frac{128.1 \times 10^{-6} \times 50 \times 1.205}{1.8 \times 10^{-5}} = 429$$

$$C_D = \frac{24}{429} + \frac{4}{429^{1/3}} = 0.586$$

$$\mathrm{X} = \frac{3L_T C_D \rho_g}{16D\rho_l} + 1 = \frac{3(0.3)(0.586)(1.205)}{16(128.1 \times 10^{-6})(1000)} + 1 = 1.31$$

$$u_T = 2[1 - X^2 + X\sqrt{X^2 - 1}] = 2\left(1 - 1.31^2 + 1.31\sqrt{1.31^2 - 1}\right) = 0.785$$

By Eq. (7.9),

$$\Delta P = -\rho_l V_T^2 \left(\frac{Q_l}{Q_g}\right) u_T = -1000 \times 50^2 \times 0.001 \times 0.785 = 1962 Pa$$

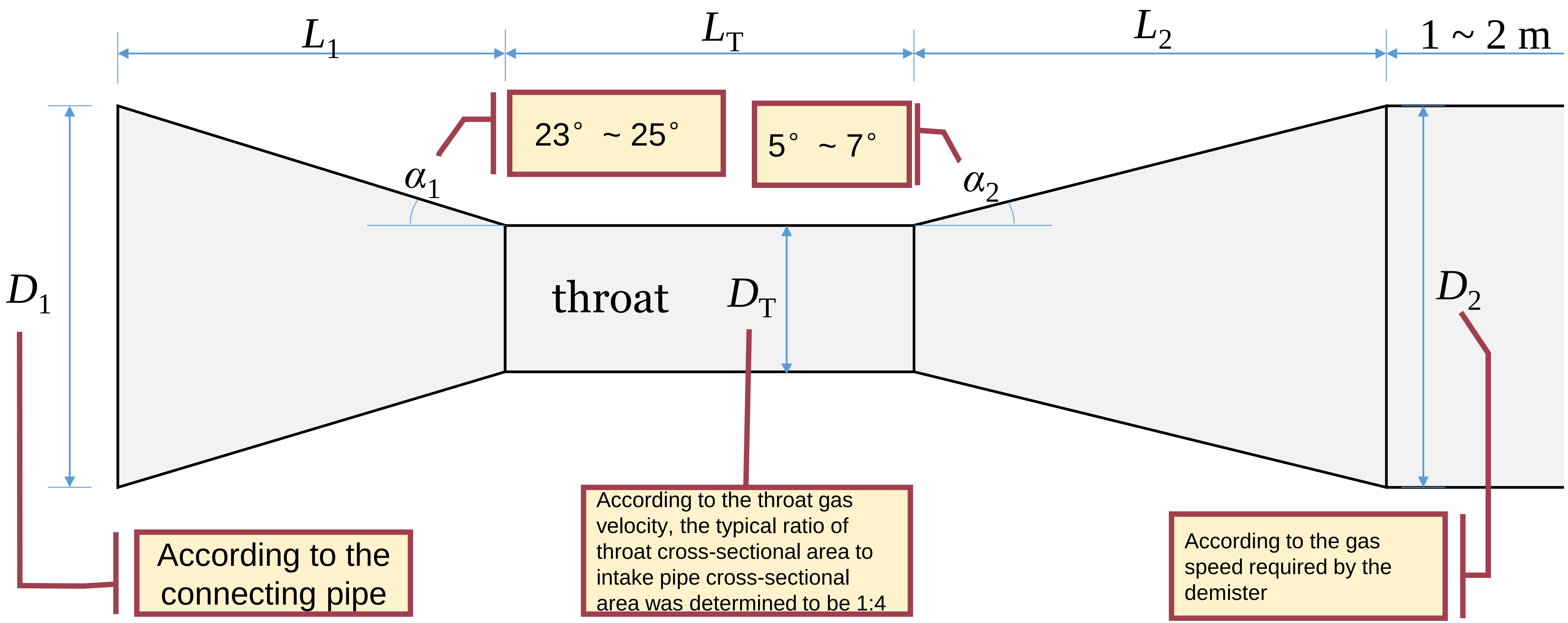
A semi-empirical equation, originally developed by Hesketh (1974) and more recently reported in the Air Pollution Engineering Manual (2000) is presented below. To use this equation, one must know the throat area, and be careful to use the units specified.

$$\Delta P = 0.863 \rho_{\mathrm{g}} A_T^{0.133} V_T^2 L^{0.78} \tag{7.13}$$

where

ΔP = pressure drop,Pa;V_T = gas velocity in throat, m/s;ρ_g = gas density, kg/m^3;A_T = throat cross-sectional area, m^2;L = liquid-to-gas ratio, L/m^3.

7.4 Design



L_1
L_T
L_2
1 ~ 2 m
23° ~ 25°
5° ~ 7°
α_1
α_2
D_1
throat
D_T
D_2
According to the connecting pipe
According to the throat gas velocity, the typical ratio of throat cross-sectional area to intake pipe cross-sectional area was determined to be 1:4
According to the gas speed required by the demister