1. SPRAY TOWER - AN INTRODUCTION

A spray tower is a scrubber which uses a liquid (typically water) to capture and remove pollutants and dust from a gaseous stream. The liquid is injected from the top of the tower by means of spray nozzels which allows for a more or less fine atomization. The drops formed, falling, meet the polluted gas rising from below, and capture the pollutants.

A typical representation of a spray tower is as follows:

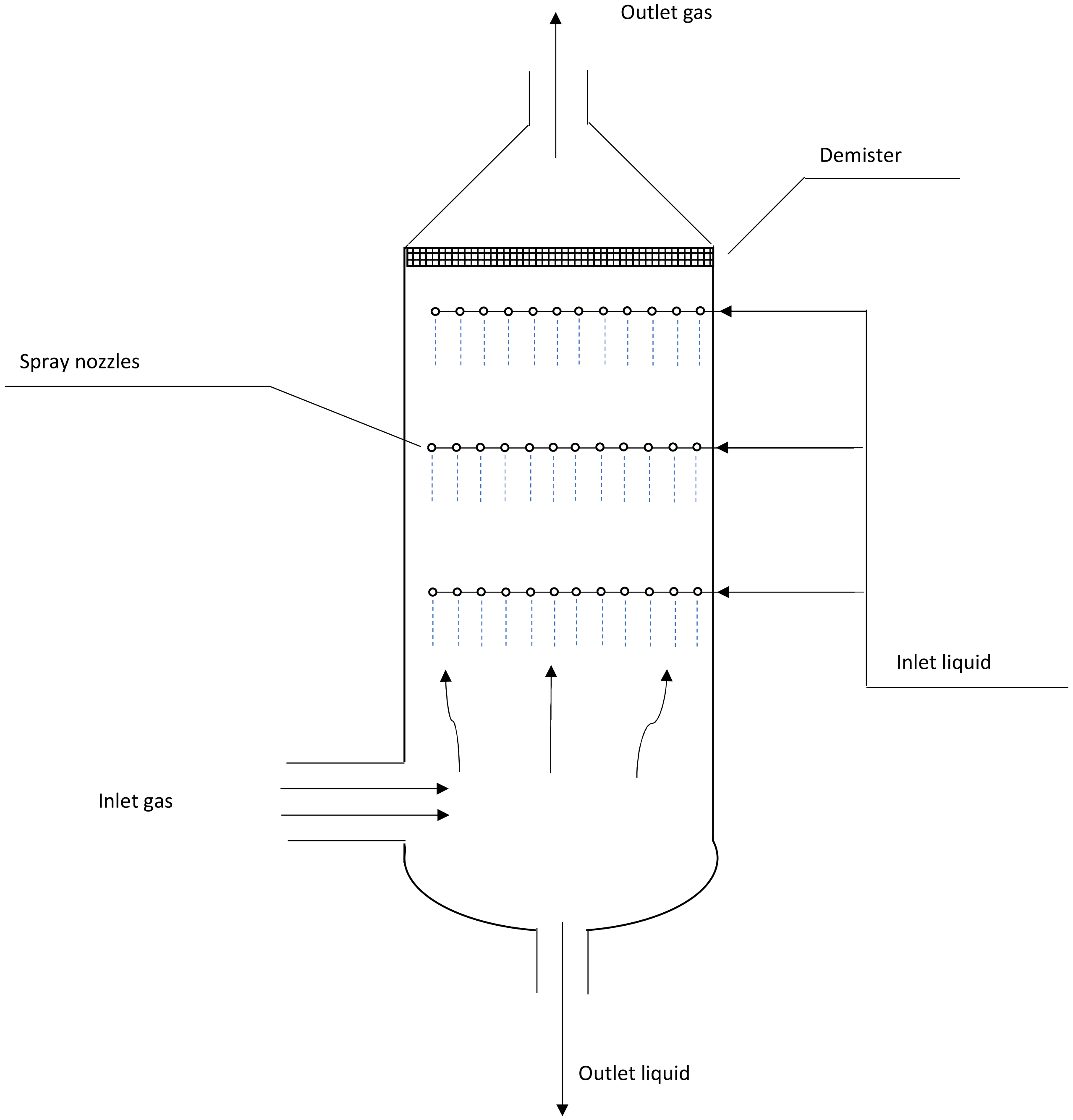


Figure 1: Spray tower

It is therefore a simple, inexpensive device with very low consumption, and for this reason, it is often used to reduce pollutants before emitting the gas into the atmosphere.

2. HOW TO USE THE CALCULATION SHEET

The spreadsheet I developed allows for a preliminary calculation of a single-stage spray column. The calculation model used is described at the end of this document (appendix A), which I invite to read for a better understanding of the approach I used. In this paragraph I briefly summarize the data to input to the program and the results it is able to show.

2.1. Input data

Once you open the spreadsheet in Excel, it will appear in an image similar to the following:

			Client		Job	
					Unit	
			Plant		Sheet	1 of 1
	SPRAY TOWER CALCULATION SHEET					V. 1.0 by M.Meloni
1	INPUT DATA FOR DESIGN POINT					
2	Gas flowrate	kg/h	13000	Gas mol. Weight		29.00
3	Inlet gas pressure	bara	1.013	Inlet gas temperature	°C	40.00
4	Gas dynamic viscosity	cp	0.0225	Solids flow	kg/h	50
5	Solid particle diameter	um	10	Particle density	kg/m3	3000
6		mm	0.01	Cunningham factor		1
7	Liquid flowrate	kg/h	31000	Liquid density	kg/m3	990.0
8	Liquid droplet diam.	um	1000	Scrubber diameter	m	2
9		mm	1	Scrubber height	m	8.0
10	Mist eliminator		YES			
11						
12						
13						
14	CALCULATION RESULTS AT **DESIGN POINT**					
15	Gas density	kg/m3	1.128	Gas volumetric flow	m3/h	11521.217
16	Solids inlet conc.	mg/m3	4339.819	Gas normal vol. flow	Nm3/h	10049.562
17	Liquid vol. flow	m3/h	31.31	Terminal velocity - Vdt	m/s	3.73537
18	Liquid/Gas ratio	lt/m3	2.72	Vdt - Vg	m/s	2.72
19	Gas velocity -Vg	m/s	1.02	Re (droplet)		187.3254
20	Stokes number		2.012	Impaction efficiency	%	72.23
21	**Solids outlet conc.**	**mg/m3**	**170.10**	**Tower efficiency**	**%**	**96.080**
22	**Tower pressure drop**	**mbar**	**4.91**			
23						
24						

The data must be entered by the user in the blue cells and only in them. Indeed, the green and white columns show data calculated by the program, which should not be changed. Below is a brief explanation of the input parameters:

- Gas flowrate: the mass flow rate of the gas entering the column
- Inlet gas pressure: pressure of the gas at the inlet of the column
- Gas dyn. Viscosity: dynamic viscosity of the gas assumed to be constant
- Solid particle diameter: The diameter of the particle entrained with the gas whose capture efficiency is to be calculated. Since in reality the entrained particles will have a variable size distribution (PSD), this diameter can be considered as the median value and for which a rather high capture efficiency is desired (ex:> 85%).
- Liquid flowrate: the mass flow rate of the liquid entering the column
- Liquid droplet diameter: average diameter of the drop of liquid produced by the spray nozzles
- Mist eliminator: if the program must take into account the presence of a demister, used only in the estimation of pressure drop
- Gas molecular weight: molecular weight of the gas
- Inlet gas temperature: temperature of the gas entering the column, always assumed constant
- Solids flow: flow rate of dust / pollutant entrained with the gas
- Particle density: density of the single pollutant particle
- Cunningham factor: Cunningham correction factor for particles less than 1 micron in diameter. For the purpose of calculating a spray tower, it can safely assumed to be always be equal to 1.
- Liquid density: density of the washing liquid
- Scrubber diameter: internal diameter of the spray tower

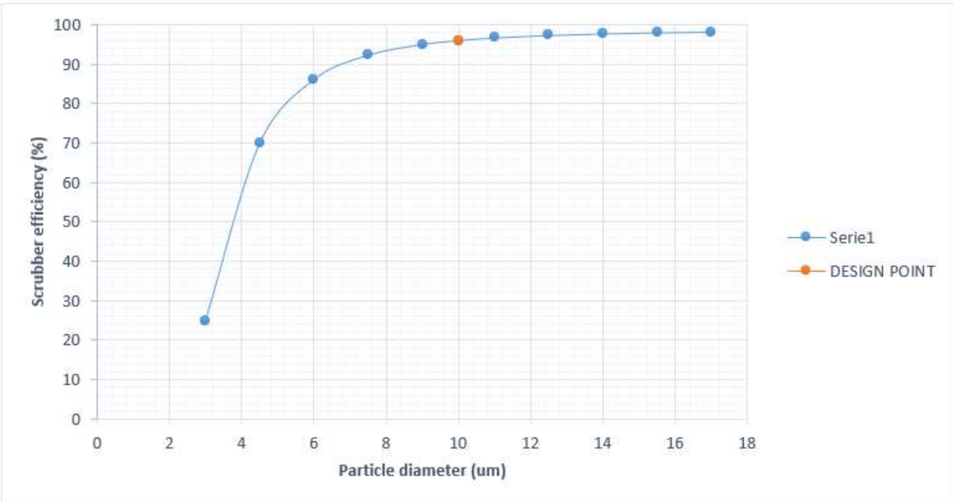
- Scrubber height: height of the part of the tower involved in the gas / liquid exchange (from the upper distributor to the bottom of the column)

2.2. Interpretation of the results

The program performs a rating calculation of a spray tower and shows the results in the “Calculation results at design points” section. The parameters highlighted in bold represent the most important data to check:

- Overall efficiency of the tower
- Outlet solids concentration
- Tower pressure drops

It is important to highlight that in this first version, all calculations are made for a specific size of the solid particle to be captured. For example, the estimated efficiency of the tower represents the capture capacity of the tower with respect to the particle of diameter X specified by the user. Smaller diameter particles will have lower capture efficiencies, while the opposite happens for larger diameter. However, I added a graph that illustrates the efficiency trend of the spray tower for particles with dimensions up to 70% lower or 70% higher than the design data.



Finally, the program suggests some values recommended by the literature for the correct sizing of a spray tower. It is strongly recommended not to go outside the recommended ranges.

Reccomended parameter for a spray tower	Recommended	Calculated
Liquid/gas ratio (l/m3)	0.7 - 2.7	2.718
Height/diameter ratio	Min. >=2	4.00
Pressure drop (mbar)	1.2 - 7.5	4.91
Droplet size (um)	500-1500	1000.00
Gas velocity (m/s)	0.3-1.2	1.019
Particle diameter (design value)	> 8 um	10.0
Tower efficiency ad design point	>85%	96.08

3. APPENDIX A - CALCULATION MODEL

The calculation model assumes that each drop produced, has a perfectly spherical shape and a defined diameter, and it moves in counter current against the gas stream entering the column. It is also assumed that there are no substantial variations in the flow rates of gas and liquid in the column or any chemical reactions.

The primary capture mechanism considered is <u>impact</u>.

A particle dragged by the gas, moving upwards with speed V_p, will have a certain probability of impacting with a drop of liquid moving downwards with speed V_d, and being dragged away with it. Not all particles will be captured in this way, however, it is assumed for the purposes of the model that this is the primary capture mechanism. It is also assumed that the speed of movement of the particle is equal to that of the gas that drags it (V_g):

$$V_p = V_g \tag{1}$$

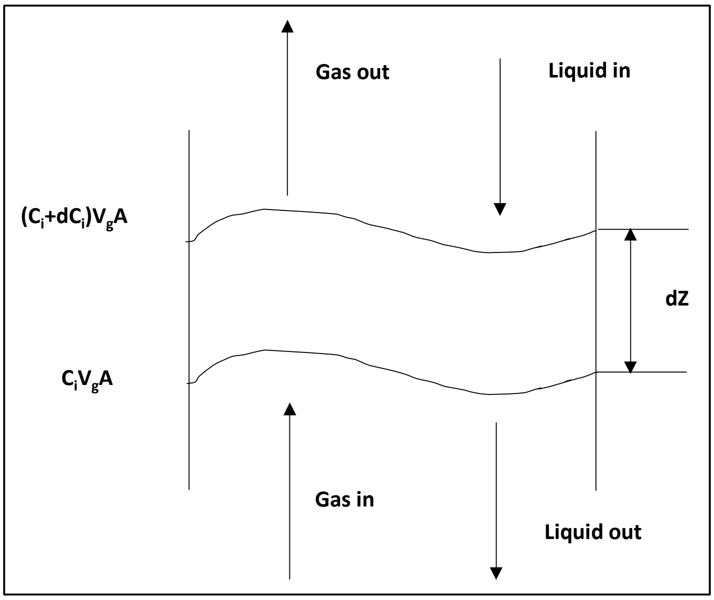


Figure 2: Mass balance of an infinitesimal section of the column

By considering a section of the tower of infinitesimal height dZ, it is possible to obtain the following material balance for the section considered:

$$C_i V_g A - (C_i + dC_i) V_g A - M_c = 0 \tag{2}$$

Where

C_i = Inlet pollutant concentration, kg/m^3

A = Tower section, m^2

M_c = Total flow rate of pollutant captured with the liquid at the bottom, kg/h

And where V_gA = Q_g, gas flowrate (m^3/h), assumed constant at the inlet and outlet for the section considered.

Now, considering that the total number of drops of liquid entering the section dZ is equal to:

$$\frac{Q_l}{\pi {d_d}^3/6} \tag{3}$$

With Q_l = incoming liquid flow, assumed equal to the outgoing (m^3/h) e d_p diameter of the liquid drop (m).

The mass of particles captured by the droplets per unit of time can be derived:

$$\eta_d V_{dt} C_i \frac{\pi {d_d}^2}{4} \tag{4}$$

Where μ_d is the removal efficiency due to the effect of a single droplet and V_{dt} is the terminal velocity of a single droplet.

At this point, an additional simplification is carried out by considering the drop-particle contact time equal to the time required for the drop to cross the section dZ:

$$dt = \frac{dz}{V_{dt} - V_g} \tag{5}$$

The total mass of particles captured by a single droplet in the unit of time is therefore equal to:

$$\mu_d V_{dt} C_i \frac{\pi {d_d}^2}{4} \frac{dz}{V_{dt} - V_g} \tag{6}$$

Multiplying (6) by the total number of drops of liquid (3) gives M_c.

By replacing the expression obtained in (2) it is therefore possible to rewrite the material balance in the following way:

$$-Q_g dC_i = \frac{3}{2}\eta_d \frac{V_{dt}}{V_{dt}-V_g}\frac{Q_l}{d_d}C_i dZ \tag{7}$$

By integrating the equation between C_0, concentration of the polluttant at inlet, and C, concentration at the end of the section considered, the following expression is obtained:

$$\frac{C}{C_0} = e^{(-\frac{3}{2}\eta_d \frac{V_{dt}}{V_{dt}-V_g}\frac{Q_l}{Q_g}\frac{Z}{d_d})} \tag{8}$$

Where $\frac{C}{C_0} = P_t$ is called penetration.

The overall efficiency of the spray tower is therefore equal to:

$$\eta = 1 - \mathrm{P}_t = 1 - e^{(-\frac{3}{2}\eta_d \frac{V_{dt}}{V_{dt}-V_g}\frac{Q_l}{Q_g}\frac{Z}{d_d})} \tag{9}$$

3.1. The Stokes number

The formula 9 obtained above allows to calculate the overall efficiency of the spray tower once all the parameters contained in the exponential are known. Of the various parameters, only one of them, η_d it is not immediately deducible but is a function of a term defined as Stokes number.

The Stokes number can be calculated using the following formula:

$$St = \frac{C_f(V_{dt}-V_g)\rho_p {d_p}^2}{18\mu d_d} \tag{10}$$

where ρ_p is the density of the particle to be captured, d^p e d_d respectively represent the average diameter of the dust particle and of the droplet, μ is the dynamic viscosity of the gas and C_f is the Cunningham correction factor, generally always assumed equal to 1 unless we consider extremely small diameters of the pollutant particles to be captured (less than 1 micron).

Several authors report in the literature the use of the following Litch and Calvert expression for the calculation of η_d:

$$\eta_d = \left(\frac{\mathrm{St}}{\mathrm{St}+\mathbf{0.35}}\right)^{\mathbf{2}} \tag{11}$$

However, in accordance with what was illustrated by Wark, Wagner and Wesley, this expression does not take into account the effects due to turbulence, and it is suggested instead the use of the following expression obtained by the authors through the Langmuir approximation:

$$\eta_d = \frac{\eta_{vis}+\eta_{pot}Re/60}{1+\mathrm{Re}/60} \tag{12}$$

Where η_{vis} e η_{pot} are the efficiencies due to flux effects at very low Re numbers (Re <1) and to Re> 2000 and whose curves as the Stokes number varies are shown in the following graph.

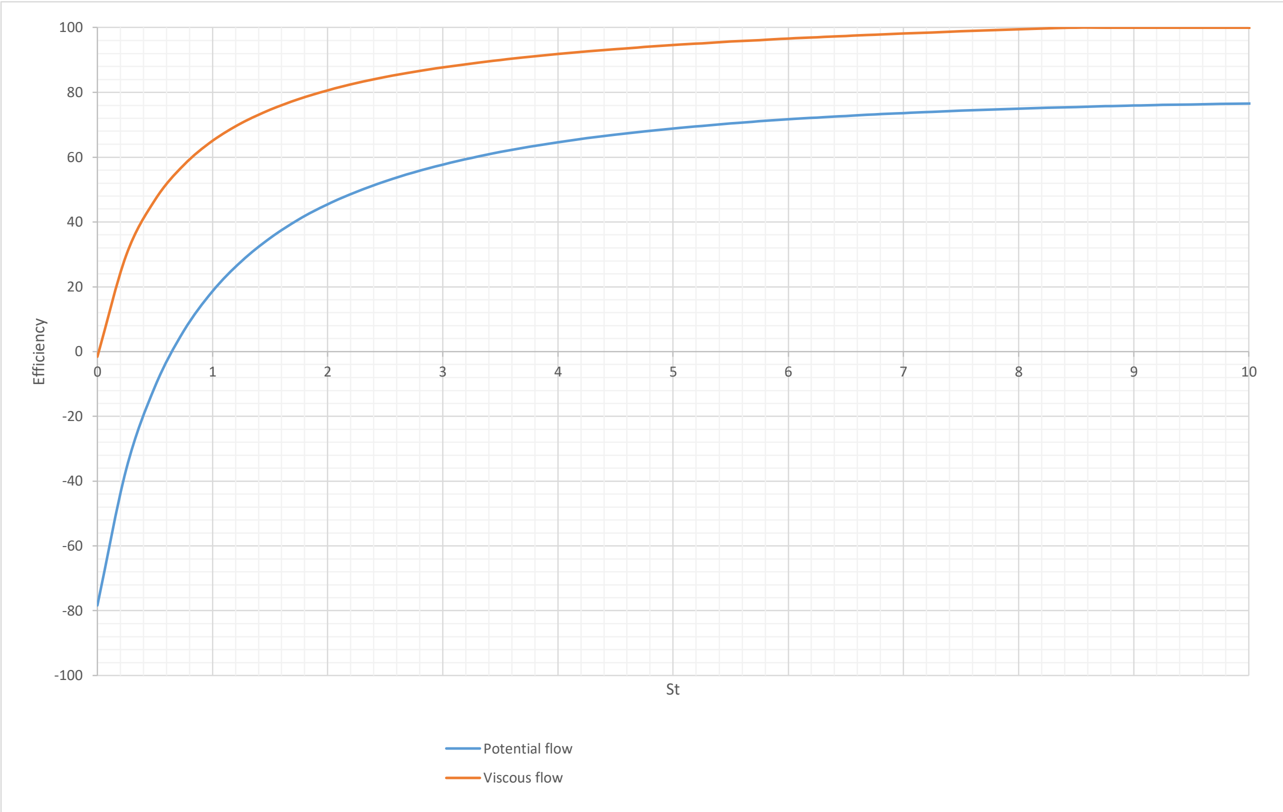


Figure 3: Langmuir approximation

The calculation sheet uses the Langmuir approximation described above to estimate the efficiency of a single droplet.

3.2. Calcolulation of the terminal velocity of the droplet

To calculate V_{dt}, terminal velocity of a single droplet, I used the well-known theoretical expression obtained by equating the force of gravity acting on the droplet with the force due to the resistance of the air during the fall:

$$V_{dt} = \sqrt{\frac{4gd_d(\rho_l - \rho_g)}{3\rho_g d_d C_d}} \tag{13}$$

Where Cd is the drag coefficient, a function of the droplet diameter and the Reynolds number. The terminal velocity V_{dt} can also be rewritten in the following three forms as a function of the Reynolds number:

- $V_{dt} = \frac{g{d_d}^2(\rho_l - \rho_g)}{18}$ valid for Re<2 (regime in which Stokes' law is valid) (14)
- $V_{dt} = \frac{2.94g^{0.71}{d_d}^{1.14}(\rho_l - \rho_g)^{0.71}}{{\rho_g}^{0.29}\mu^{0.43}}$ valid for Re between 2 and 500 (transition region) (15)
- $V_{dt} = 1.74\sqrt{\frac{gd_d(\rho_l - \rho_g)}{\rho_g}}$ for Re>500 (Newton's law) (16)

With $Re = \frac{\rho_g V_{dt} d_d}{\mu}$ (17)

And μ dynamic viscosity of the gas phase.

The calculation is carried out iteratively assuming first an educated guess for the terminal velocity, calculating Re and iterating until convergence.

3.3. Pressure losses

The overall pressure drop of the spray tower is calculated in the following way:

$$\Delta P_{tot}=\Delta P_{friction,dry} + \Delta P_{elevation} + \Delta P_{wet} + \Delta P_{demister} \tag{18}$$

Where:

- $\Delta P_{friction,dry}$, contribution due to the passage of the gas phase in the spray tower assumed empty and in the absence of liquid, increased by concentrated losses due to entry and exit into the column;
- $\Delta P_{elevation}$, contribution due to the rising gas in the tower (geodetic difference);
- ΔP_{wet}, contribution due to the presence of the liquid that descends into the column in the form of droplets;
- $\Delta P_{demister}$, possible contribution due to the presence of a mist eliminator at the top of the column;

The first two terms are calculated respectively by applying the well-known Darcy-Weisbach relation ($\Delta P_{friction,dry}$) while for $\Delta P_{elevation} = \rho_g gZ$.

For ΔP_{wet}, assuming the following:

- The droplets forming the liquid phase are spherical, all of the same size and impenetrable. They can therefore be approximated to solid particles that obstruct the path of the gas;
- Between the gas and liquid phases there is a relative velocity which is always constant, equal to V_{dt}. This is equivalent to say that assuming the liquid phase is not moving, the gaseous phase moves towards the liquid particles with velocity V_{dt};
- The drops occupy a volume that can be considered constant at any time, given by the product of the liquid flow rate that descends from the column for the passage time (integration of formula 5 over the entire height of the tower Z);

In this way, the liquid phase is approximated to a solid phase with a high degree of vacuum and ΔP_{wet} is calculated with a variant of the Ergun equation:

$$\Delta P_{wet} = \frac{V_{dt}}{d_d}\left(\frac{1-\varphi}{\varphi^3}\right)\left(\frac{150(1-\varphi)\mu_g}{D_d} + 1.75\rho_g V_{dt}\right)Z \tag{19}$$

With φ void fraction and Z tower height.

Finally $\Delta P_{demister}$ is obtained by the following equation:

$$\Delta P_{demister} = 1.8061 V_g - 0.1912 \tag{20}$$

whose parameters have been obtained by interpolating the data coming from some suppliers of mist eliminators (unit of measure: Pa).

4. References

1. Perry's Chemical Engineers' Handbook, 8th edition, Don Green, Robert Perry
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3. Particulate Matter Controls, EPA, chapter 6

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7. Fundamentals of Air Pollution, Richard W. Boubel, Donald L. Fox, Bruce Turner
8. Air pollution control equipment calculations, Luis Theodore
9. Air Pollution, its Origin and Control, Wark K., Warner C. F. and Wesley A.