EXERCISES

FOR THE COURSE
“AIR POLLUTION CONTROL”

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1. GENERAL CONCEPTS AND FUNDAMENTALS

1.1. Vehicular exhaust emissions

The following pollutant is not contained in the vehicular exhaust emissions:

a) Lead
b) Ammonia
c) Carbon monoxide
d) Particulate matter

1.1.1 Solution

b) ammonia. Vehicular Exhaust is one of the main pollutants in air in the urban areas today. In fact, in most cities it is the main polluter. In India this has become a major problems and the government has been trying to introduce various initiatives to ensure that vehicular pollution levels can be brought down to acceptable levels.

1.2. Leaded petrol

Earlier, leaded petrol used to be the most widespread, though easily preventable, source of urban air pollution in the world. According to WHO (World Health Organization), 15–18 million children in the developing countries are already suffering from permanent brain damage due to lead poisoning. Why is tetra-ethyl lead added to petrol?

a) It prevents engine knocking
b) Reduces vehicular emissions
c) Increases life of motor tyres
d) None of the above

1.2.1 Solution

a) It prevents engine knocking. Tetra-ethyl is an additive to petrol that prevents engine knocking and increases the octane rating of petrol, leading to better vehicle performance. It is also the most widespread, easily preventable source of urban air pollution.

1.3. Bhopal gas tragedy

Bhopal gas tragedy struck in the year 1984 due to the leakage of the following gas:

a) methyl-iso-cyanate
b) nitrous oxide
c) methane
d) carbon monoxide

1.3.1 Solution

a) methyl-iso-cyanate (CH_3NCO) . On Monday, 3 December 1984, a major tragedy occurred in Bhopal, India, when a poisonous vapour, a highly toxic cloud of methyl isocyanate, burst from the factory of the Union Carbide pesticide plant. More than 2000 died immediately, and as many as 3 00 000 were injured. In addition, animals and the environment around the area were affected. Even today studies show that many of the survivors were still suffering with various health problems.

1.4. Evaluation carbon dioxide from car

Assume an average car in Italy gets 15 km per liter, is driven 15.000 km per year and weighs 1500 kg. Further, assume that gasoline weighs 0,75 Kg per liter and contain 85% carbon by weight. Is there any truth to the statement that each car emits its own weight in carbon dioxide each year? Estimate the carbon dioxide emission

1.4.1 Solution

A simplified equation for the combustion of a hydrocarbon fuel may be expressed as follows:
Fuel (C_XH_Y) + oxygen (O_2) + spark = water (H_2O) + carbon dioxide (CO_2) + heat
As carbon has an atomic weight of 12 and oxygen has an atomic weight of 16, CO_2 has a molecular weight of 44 (1 carbon atom [12] + 2 oxygen atoms [2 x 16 = 32]).
Therefore, CO_2 is 3.67 times heavier than carbon (44 ÷ 12 = 3.67).
The carbon contained in the gasoline burned annualy is equal to:
(15000 km/year ÷ 15 km/l)* 0,75 kg/l * 0.85 % = 637.5 kg C/year
The carbon dioxide emitted is:
637,5 kg C/year * (44 MW CO_2 /12 MW C) = 2337,5 kg CO_2/year
So the average car emits **much more** than its own weight in carbon dioxide each year.

1.5. Water vapour pressure

An air stream contains up to 3% by volume of water vapour at ambient temperature. What is the partial pressure of the water vapour?

1.5.1 Solution

p_{H2O} = 1 atm *0.03= 0.03 atm.

1.6. Partial pressure

An air stream contains 1% by volume of water vapour and 1,000 ppm H_2S. What are the partial pressure of the water vapour and H_2S?

1.6.1 Solution

p_{H2O} = 1/100 x 1 = 0.01 atm; p_{H2S} = 1000/1000000 x 1 = 0.001 atm.

1.7. Units conversion

Assume that the Air Quality Standard for Ozone (MW=48) is 0.075 ppm in 8 hours and for sulfur dioxide (MW=64.06) is 0.14 ppm in 24 hours.

a) What are the AQSs for ozone and sulfur dioxide expressed in µg/m^3 at 25°C and 1 atm?
b) Assume that a sample of air at 25°C and containing SO_2 gas at a concentration equal to the AQS is raised to 150°C. What is its SO_2 concentration at 150°C in ppm and µg/m^3

1.7.1 Solution

You have to apply the following equation:

$$C_{mass} = \frac{M_P}{V_t} = \frac{C_{ppm} * MW_P}{R * T/P}$$

Where:

- C_{mass}= mass concentration, µg/m^3
- C_{ppm}= volume or molar concentration, ppm
- M_p= mass of pollutant gas, µg
- MW_p= molecular weight of pollutant gas, g/gmol
- T= temperature, K
- P = preassure, Pa
- R= 8.314 Pa*m^3/gmol*K

Question a)
Ozone →Cmass=147,2 µ/m3
Sulfur dioxide →Cmass= 366,7 µ/m3
Question b)

Sulfur dioxide → Cppm=0.14 µg/m3 (the same!! relative measure)
Sulfur dioxide →Cmass=258,3 µ/m3

1.8. Volume flow rates conversion

Convert a flow rate Q of 10 Nm^3/h at standard conditions of 0 °C, 1 atm (earlier IUAPC definition) to actual stack gas conditions (180°C, 0.9 atm).

1.8.1 Solution

$$Q_a = Q_n * \frac{P_n * T_a}{P_a * T_n} = 10 * \frac{1 * (273 + 180)}{0.9 * 273} = 18.43\ m3/h$$

1.9. Mass concentration conversion

Convert a concentration C of 20 mg/m^3 from actual conditions (100 °C, 1 atm) to STP (earlier IUAPC definition) reference conditions (0°C, 1 atm).

1.9.1 Solution

$$C_n = C_a * \frac{P_n * T_a}{P_a * T_n} = 20 * \frac{1 * (273 + 100)}{1 * 273} = 27.32\ mg/m3$$

1.10. Mass concentrations and volume flow rates conversion: reference conditions (1)

$Q_{v,a}$ = 5 $m^3{}_a/h$, CO = 10 $mg/m^3{}_a$, U = 15% by volume. Calculate:

a) CO concentration on dry volume basis; b) $Q_{v,db}$; c) CO mass flow rate

1.10.1 Solution

a)

$$C_{CO,db} = \frac{C_{CO,a}}{(1 - \frac{U}{100})} = \frac{10}{(1 - \frac{15}{100})} = 11.8\ mg/m3$$

b)

$$Q_{v,db} = Q_{v,a} * (1 - \frac{U}{100}) = 5 * (1 - \frac{15}{100}) = 4.25\ m3/h$$

c)

CO mass flow can be calculated either using actual O2 conditions than reference O2 conditions:

Actual condition: $M_{CO} = C_{CO,a} * Q_{v,a} = 10\frac{mg}{m3} * 5\ m3 = 50\ mg/h$

Reference conditions: $M_{CO} = C_{CO,ref} * Q_{v,ref} = 11.8\frac{mg}{m3} * 4.25\ m3 = 50\ mg/h$

1.11. Mass concentrations and volume flow rates conversion: reference conditions (2)

Natural gas fuelled turbine:

$Q_{v,db}$ = 45,000 $m^3{}_n/h$, NO_x = 400 $mg/m^3{}_{n,db}$, $O_{2,a\ db}$= 13%. Calculate:

a) NO_x concentration at $O_{2\ ref}$ = 15%; b) $Q_{v,O2\ ref}$; c) NO_x mass flow rate M

1.11.1 Solution

a)

$$C_{n,db,O2\ ref} = C_{n,db,O2\ a} * \frac{21 - O_{2\ ref}}{21 - O_{2\ a}} = 400 * \frac{21 - 15}{21 - 13} = 300\ mg/m3$$

b)

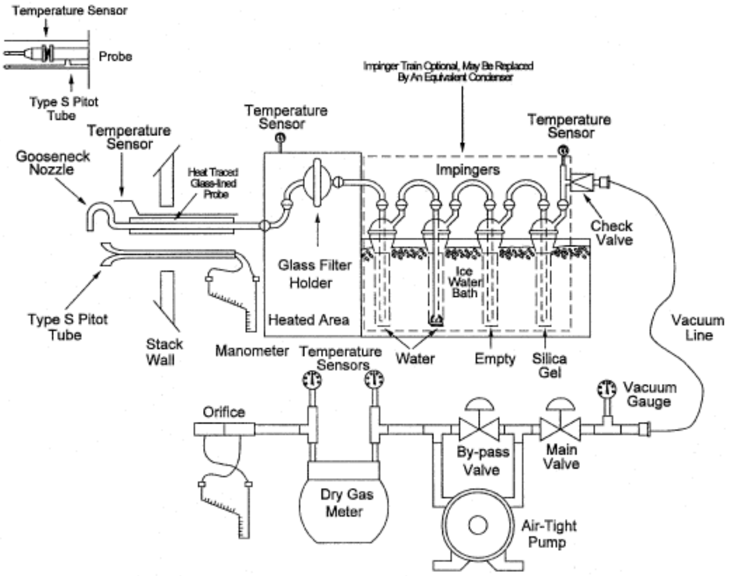
$$Q_{v,db,O2\,ref} = Q_{v,db,O2\,a} * \frac{21 - O_{2\,a}}{21 - O_{2\,ref}} = 45000 * \frac{21-13}{21-15} = 60000\ m3/h$$

c)
NOx mass flow can be calculated either using actual O2 conditions than reference O2 conditions:
Actual condition: $M_{NOx} = C_{NOx,a} * Q_{v,a} = 400 \frac{mg}{m3} * 45000\ m3 = 18\ kg/h$
Reference conditions: $M_{NOx} = C_{NOx,ref} * Q_{v,ref} = 300 \frac{mg}{m3} * 60000\ m3 = 18\ kg/h$

1.12. Mass concentrations and volume flow rates conversion: reference conditions (3)

A sample stream of dry gas is being withdrawn from a stack. The stack gases are at 200°C and 730 mm Hg. The stream flows through a heated filter, a set of cooled impingers, a small air pump and then through a flow meter (see figure of particulate sampling apparatus).
The rate of flow is determined to be 30.0 liters/minute at 20°C and 790 mm Hg.

a) Calculate the actual volumetric flow rate through the filter (at 200°C and P=730 mm Hg)
b) If 1.42 mg of solid particles are collected on the filter in 30 minutes, calculate the concentration of particles in the stack gas (in µg/m^3)



1.12.1 Solution

$$Q_a = Q_n * \frac{P_n * T_a}{P_a * T_n} = 30 * \frac{790 * (273+200)}{730 * (273+20)} = 52.4\ l/m$$

In 30 minutes the volume is 52.4 *30 = 1.572 m3

$$Concentration\ (\frac{\mu g}{mc}) = \frac{1.42\ mg}{1.572\ mc} * 1000 = 903\ \mu g/mc$$

1.13. Pollutant concentration normalisation

Continuous emission monitoring of a waste gas at the stack exit sampling point gives:
[SO2] = 76.4 mg/m3
Volumetric flow rate, G = 60,000 m3/h
Temperature = 123 °C
Pressure = 102 kPa
Calculate:
a) the C_{SO2} in mg/Nm3 (Pressure 1 atm; T=0°C)

b) the volumetric flow rate in Nm3/h
c) the gas exit speed, if the inner stack diameter at the sampling point is 1.0 m.

1.13.1 Solution

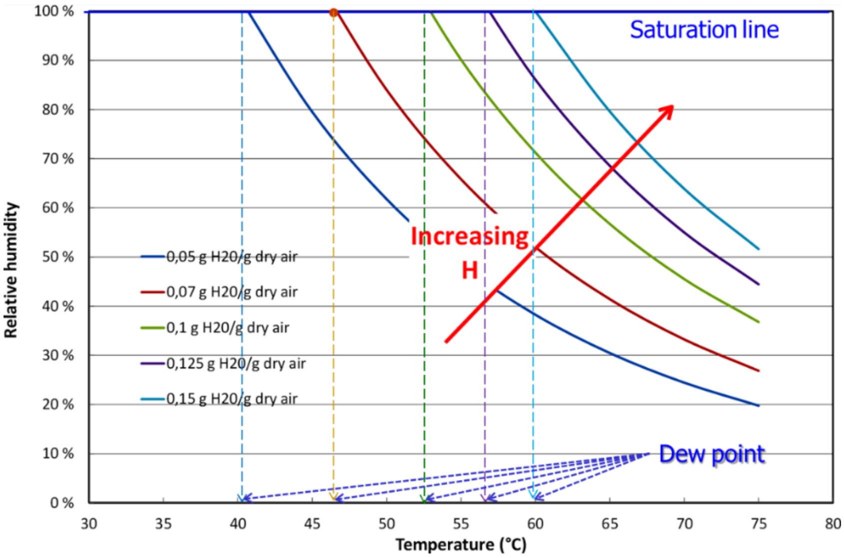
One of the problems of the waste gas emissions is, always, the correction to be applied to the measured pollutants concentrations, according to the temperature and pressure (concentration normalization).
Generally, EXIT FLUE GAS is at relatively high temperature (100 -150°C), P close to 1.0 atm, contains some water vapour (10%), and the O2 content may be < or > than 15%.
WE MUST CONVERT THE MEASURED CONCENTRATIONS OF POLLUTANTS TO THE CONDITIONS SET BY THE COMPETENT AUTHORITY, BY USING SPECIFIC FORMULAS.
a) [SO2] = 110.1 mg/Nm3
b) F = 41,649 Nm3/h
c) v =21.2 m/s [v=G/A=(60000/3600)/(3.14x1.02/4)]

1.14. Acid Dew Point

Because of the presence of gaseous sulfuric acid, the sulfuric acid dew point of most flue gases is much higher than the water dew point of the flue gases.
Calculate the water dew point for a flue gas with 12 volume % water vapour and containing no acid gases.
Calculate the dew point of the same flue gas with the addition of only 4 ppmv (0.0004 volume %) of SO3.

1.14.1 Solution

12 volume % water vapor = (12/100)*18/29=0,07 g water/gdry air
From the following figure the flue gas has a water dew point of about 49.4 °C



The same flue gas with the addition of only 4 ppmv (0.0004 volume %) of SO3 will have a sulfuric acid dew point of about 130.5 °C. You have to apply the following expression:
1000/T=2.276−0.02943loge(PH2O)−0.0858loge(PSO3)+0.0062loge(PH2O)loge(PSO3)

1.15. Dew point

Propane gas C_3H_8 is reacted with air such that the dry product gases are 11.5 percent CO2, 2.7 percent O2, and 0.7 percent CO by volume.
What percent theoretical air was supplied?
What is the dew point temperature of the products if the product pressure is 100 kPa?

1.15.1 Solution

See resolution of Example 4 in fundamentals
The dew point temperature for the product gases is the temperature at which the water in the product gases would begin to condense when the products are cooled at constant pressure. The dew point temperature is equal to the saturation temperature of the water at its partial pressure in the products.

$$T_{\mathrm{dp}} = T_{\mathrm{sat}} \text{ at } P_v = y_{\mathrm{v}} P_{\mathrm{products}}$$

$$y_v = \frac{N_{\mathrm{water}}}{\sum_{\mathrm{products}} N_e}$$

Determine dew point temperature of the products for Example 4.

$$y_v = \frac{4}{2.83 + 0.17 + 0.66 + 4 + 20.96} = 0.1398$$

$$P_v = y_v P_{\mathrm{products}} = 0.1398(100\,kPa)$$

$$= 13.98\,kPa$$

$$T_{\mathrm{dp}} = T_{\mathrm{sat}} \text{ at } 13.98\,\mathrm{kPa}$$

$$= 52.31^o C$$

What would happen if the product gases are cooled to 100°C or to 30°C?

1.16. Absorption of competitive species: SO_2 vs CO_2

A flue gas contains 44,000 ppm of CO_2 and 300 ppm of SO_2; the scrubbing liquor pH is 7. Flue gas stream: 42,500 m3/h (= 11.8 m3/s), at 66 ºC. Blow-down: 1.0 m3/h (liquor discharged).
At pH 7: KH(CO_2) = 0.2 M/atm; KH(SO_2) = 3 x 105 M/atm. (Both: Heff !)

a) Calculate $[CO_2]$aq.;
b) To keep (SO_2)g < 5 ppm in the cleaned gas, what can be the max SO_2 concentration in the scrubbing liquor?
c) the amount of SO_2 to be removed in mol/h, and kg/h;
d) $[SO_2]$aq in the scrubbing liquor (= blow-down conc.!).

1.16.1 Solution

A) CO_2 (g)=44,000 ppm = 4.4% v/v; PCO_2=xCO_2 P =0.044 x 1 = 0.044 atm
$[CO_2]$aq = KH PCO2
$[CO_2]$aq = 0.2 x pCO_2 = 0.2 x 0,044 = 8.8 mM (=0.4 g/L; CO_2 absorbed < 1%)

B) SO_2 (g) = 5 ppm; PSO2 = xSO_2. P = 5 . 10-6 . 1 = 5.0 . 10-6 atm
$[SO_2]$aq in eq. with SO2 gas 5 ppm = KH PSO2
$[SO_2]$aq = 3 .105 M/atm x 5 .10-6 atm = 1.5 M =96 g/l (max. conc. in solution in eq. with 5 ppm SO_2 in the gas phase)

C) SO_2 (g) to be removed: (300-5) ppm x 42,500 m3/h = 12.5 m3/h (T=66°C; p=1atm) = 0.45 kmol/h = 28.8 kg SO2/h

D) Concentration of "SO_2" in the liquor:
$[SO_2]$aq blowdown = Nr moles /Volume = 0.45 kmol/h / 1.0 m3/h = 0.45 mol/L = 0.45 M
Note 1. The system can really work! In fact, the conc. of SO_2 in the blow-down liquor is < than the maximum conc. permitted by Henry law, that is 1.5 M. If SO_2 conc. in the blow-down is > than 1.5 M, you cannot reduce the SO_2 conc. down to 5 ppm in the cleaned gas ! The higher the blow-down, the lower the pollutants concentrations in the cleaned gas!)
Note 2. At pH 7 there is no SO_2 in the aq. phase, but only HSO_3- (≈70%) and $SO3^{2-}$ (≈30%) (see next figure)

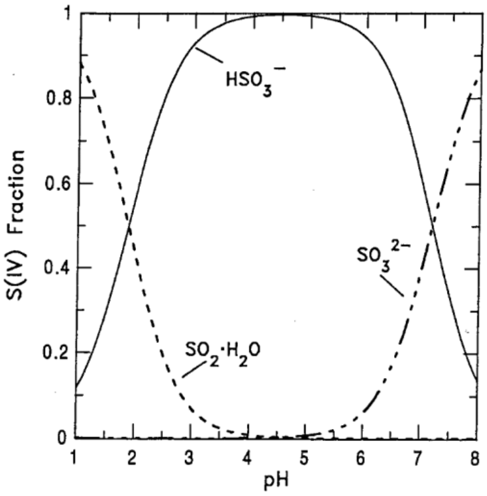


Figure. Concentration of S(IV) species expressed as S(IV) mole fraction. These fraction are independent of the gas-phase SO_2 concentration

1.17. Concentration of NO_X in the troposphere

Considering the Pianura Padana, why the concentration of NOX in the troposphere is higher in winter than in summer?

1.17.1 Solution

In the summer house heating is not present and auto clean processes are faster (see Arrhenius law)

1.18. Acidity of SOx

Coal and fuel oil contain compounds of sulfur. For the purposes of stoichiometric calculations this is assumed to burn to sulfur dioxide:
$S + O_2 \rightarrow SO_2$
In reality a mixture of sulfur dioxide and a small amount of sulfur trioxide (SO_3) is produced, but it is conventional to assume combustion to SO_2 when calculating air requirements.
Do you think that the presence of SO3, instead of SO2, could reduce the wet-scrubbing efficiency of sulfur oxides with alkaline compounds ($NaOH/Ca(OH)_2/CaCO_3$)?

1.18.1 Solution

NO ; because SO_3 IS A STRONGER ACID THAN SO_2, HENCE NEUTRALIZATION PROCESSES YET MORE EFFICIENT!
pKa H_2SO_3= 1.9
pKa H_2SO_4= -3.0

1.19. Units of ppm

Though neither Emission Limit Values, nor Air Quality Limits have been set in ppm in the EU legislation, this unit is currently used. Can you tell me one reason?

1.19.1 Solution

Because ppm are not temperature dependent; also, very useful in calculating moles, partial pressures, etc.

1.20. Density of gases

The relative density of a gas compared with dry air (same T and P) is very useful data. Can you write down the formula for such calculation?
The "MW" of dry air is 29; calculate the "MW" of humid air with 3% of water vapour ($MW_{(H2O)}$ = 18)

1.20.1 Solution

$\rho_{rel} = D_{gas}/D_{dry\ air} = MW_{gas}/MW_{dry\ air}$
$\rho_{rel} = D_{Humid\ Air}/D_{dry\ air} = MW_{humid\ Air}/MW_{dry\ air}$ = (97% 29 + 3% 18)/29 = 28,67/29 = 0.99

1.21. Density of gases

Version a)
Calculate the Ratio (R) of $V_{flue\ gas}/V_{CH4}$ (same T and P) for the stoichiometric combustion of methane (air composition: 79% of N2 and 21% O_2 (v/v).
Calculate also R at $T_{fluegas}$ = 400°C and T_{air} = 20°C

Version b)
Calculate the Ratio (R) of $V_{flue\ gas}/V_{Octane}$ (same T and P) for the stoichiometric combustion of octane; air composition: 79% of N2 and 21% O_2 (v/v).

1.21.1 Solution

Version a)
R = 10.5
$CH_4 + 2\ O_2 = CO_2 + 2H_2O$
$1VCH_4 \rightarrow 1VCO_2 + 2VH_2O + 2 \times 79/21\ VN2 = 3 + 7.5 = 10.5$ V FLUE GAS; …..

Version b)
Solution
R=64
$C_8H_{18} + 25/2\ O_2 \dashrightarrow 8CO_2 + 9\ H_2O$
1V C8H18 ---> 8V CO_2 +9V H_2O+ 25/2 x 79/21 VN_2= 8+9+47=64 V FLUE GAS; …..

1.22. Sub-stoichiometric (in air) air-to-fuel (A/F) ratios in modern engines

Sub-stoichiometric (in air) air-to-fuel (A/F) ratios *(also called fuel-rich, or λ<1, slightly less than 1!)* occur in all modern engines fuelled by gasoline, because it is required by the TWC (three way catalysts). Does this combustion condition favour, or not, the production of high concentrations of NOx in the exhausted gas?

1.22.1 Solution

NO, because $N_2 + O_2 = 2\ NO$ (shifted to left, because of virtual absence of O2);

Note: While rich-burn engines can operate on a broad variety of natural gas fuels, alternative gases like **biogas, sewage gas, or landfill gases** cannot be used because they could poison the three-way catalyst. Lean-burn combustion is generally adopted for alternative gases (as diesel engine do!). Lean-burn engines use a lot of excess air, usually up to twice the amount needed for complete fuel combustion. This air dilution effectively cools down the peak combustion temperatures in the cylinder; that reduces the NOx production and allows low engine-out emissions without the need for an after treatment system in many applications. New leanburn engines (diesel fuelled cars and lorries), however, require selective catalytic converters with urea injection (EURO 6)!

1.23. Le Chatelier's principle

What reaction conditions would be more favourable for chemical conversion of NO into NO2?
$2\ NO\ (g) + O_2\ (g) = 2\ NO_2\ (g)$
A) high temperature, high pressure

B) low temperature, high pressure
C) high temperature, low pressure
D) low temperature, low pressure
E) neither temperature nor pressure will affect the equilibrium

1.23.1 Solution

Use the Le Chatelier principle
The reaction is exothermic. For an exothermic reaction, heat is essentially a product of the reaction. In keeping with Le Chatelier's principle, if you increase the temperature you are increasing the amount of products, and so you shift the balance at equilibrium back toward reactants, meaning there will be more reactants left at equilibrium. The higher the temperature goes, the further the balance at equilibrium shifts back toward reactants. In exothermic reactions, increase in temperature decreases the equilibrium constant, K.
With a pressure increase due to a decrease in volume, the side of the equilibrium with fewer moles is more favorable.
So the correct answer is low temperature, high pressure

1.24. Degradation of pollutant in atmosphere

In the summer period, because of higher air temperature the chemical (and photo-chemical) degradation of air pollutants is faster or slower.

1.24.1 Solution

Faster

1.25. Degradation of pollutant in atmosphere

Photolytic degradation processes of air pollutants are more favourable in the summer period, or during the winter (SUMMER / WINTER)? Why?

1.25.1 Solution

Photolytic processes are not temperature dependent!

1.26. Relative humidity

The saturation pressure of water vapour in the air at 60°C is 19.9 kPa. In a waste gas the water content is 15% by volume.
A) Calculate the relative humidity: RH = ……. % (hint: 1 atm = 101.3 kPa)

1.26.1 Solution

$$RH(\%) = 100 * \frac{p_{H_2O}}{p_{v,H_2O}{}^{\circ}} = 100 * \frac{0.15 * 101.3}{19.9} = 76\%$$

1.27. Relative humidity

Assuming a temperature of t=110 °C, a total pressure of 1 atm and a absolute humidity of 0.1 kg water/kg dry air, estimate the relative humidity?
For the vapor pressure of water use the following table.

Temperature	**Water saturation pressure**		
[°C]	**[kPa], [100*bar]**	**[atm]**	**[psi]**
0.01	0.61165	0.0060	0.088712
2	0.70599	0.0070	0.10240
4	0.81355	0.0080	0.11800
10	1.2282	0.0121	0.17814

Temperature	**Water saturation pressure**		
[°C]	**[kPa], [100*bar]**	**[atm]**	**[psi]**
14	1.5990	0.0158	0.23192
18	2.0647	0.0204	0.29946
20	2.3393	0.0231	0.33929
25	3.1699	0.0313	0.45976
30	4.2470	0.0419	0.61598
34	5.3251	0.0526	0.77234
40	7.3849	0.0729	1.0711
44	9.1124	0.0899	1.3216
50	12.352	0.122	1.7915
54	15.022	0.148	2.1788
60	19.946	0.197	2.8929
70	31.201	0.308	4.5253
80	47.414	0.468	6.8768
90	70.182	0.693	10.179
96	87.771	0.866	12.730
100	**101.42**	**1.001**	**14.710**
110	143.38	1.42	20.796
120	198.67	1.96	28.815
130	270.28	2.67	39.201
140	361.54	3.57	52.437
150	476.16	4.70	69.061
160	618.23	6.10	89.667
180	1002.8	9.90	145.44
200	1554.9	15.35	225.52

(source: https://www.engineeringtoolbox.com/water-vapor-saturation-pressure-d_599.html)

1.27.1 Solution

$$RH(\%) = 100 * \frac{29 * H * p}{p_{v,H_2O}{}^{\circ} * (18 + H * 29)} = 9.5$$

1.28. Relative humidity

Humid air at 60°C, 1 atm, and 73 % relative humidity is fed into a unit operation at a rate of 500 m^3/h. The vapor pressure of water at 1 atm (101,300 Pa) and 60◦C is $p_{v,H20}°$=19,920 Kpa.
Determine

- the molar flow rates of water, dry air, and oxygen, assuming oxygen makes up 21% of dry air.
- The absolute humidity

1.28.1 Solution

a) the molar flow rates of water, dry air, and oxygen, assuming oxygen makes up 21% of dry air
First we must determine the partial pressure of the water with the Raoult's Law:
p_{H2O} = HR· $p_{v,H20}°$ = (0.73)·19,920=14,540 Pa
We can find now the vapour mole fraction of the water:
y_{H2O}= p_{H2O} /P = 14,540 Pa /101,300 Pa = 0.1435 mol $_{H2O}$/mol
Assuming the humid air behaves ideally, we can use the ideal gas law to solve for the molar flow rate of the wet air:
ntotal = PV/RT= (101,300 Pa)*(500 m3h)/(8.314m3·Pamol·K)(333.15 K) =18,300 mol/h
Since we know the mole fraction of the water, we can solve the mole fraction of the dry hair by:
y_{dry}=y_{wet}−y_{H2O} = (1−0.1435) =0.8565 mol dry air/ mol
Since the mole fraction of oxygen in dry air is y_{oxy}=0.21, we can finally solve for the molar flow rate of water, dry air, and oxygen:
n_{H2O}=n_{total} * y_{H2O}=(18,300 mol/h)*(0.1435 mol $_{H2O}$/mol)=2.626 kmol/h
n_{dry}= n_{total} * y_{dry} =(18,300 mol/h)*(0.856 mol $_{dry}$/mol)=15.67 kmol/h
n_{oxy}= n_{total} * y_{oxy} =(18,300 mol/h)*(0.856 mol $_{dry}$/mol) *(0.21 mol $_{doxy}$/mol$_{dry}$) =3.29 kmol/h

b) absolute humidity
We have already solved for the partial pressure of the water vapor so solving for the molal humidity

$$H = \frac{m_{H_2O}}{m_{dry\ air}} = \frac{18 * p_{H_2O}}{29 * (p - p_{H_2O})} = \frac{18 * 14550}{29 * (101300 - 14550)} = 0.104\ kgH2O/kgdry$$

1.29. Antoine's equation

Find the temperature at which the vapour pressure of water is 6,000 Pa.

1.29.1 Solution

Using Antione's equation with the values reported in the slide of lectures we obtain a value of 309K.

1.30. Combustion of waste

Calculate the theoretical amount of oxyge required for the complete combustion of 1000 kg of waste, with the composition C_5H_5N (At. Weights: C = 12; H = 1; N = 14).

- Write the balanced combustion equation.
- Calculate the stoichiometric amount of air ($V_{\text{stoich. air}}$ in Nm^3) at n.c. - 0°C, p = 1.0 atm.

1.30.1 Solution

The MW of the waste is 79.
Write the balanced combustion equation**:** $C_5H_5N + 12.5/2\ O_2 = 5\ CO_2 + 5/2\ H_2O + 1/2\ N_2$
Calculate the stoichiometric amount of air (n.c. *- 0°C, p = 1.0 atm*): $V_{\text{stoich. air}}$ = 10,132 Nm^3
n_{C5H5N} = 1000/79 = 12.66 kmol;
n_{O2} = 12.5/2 x n_{C5H5N} = 6.25 x 12.66 = 79.125 kmol;
Considering the molar fraction of oxygen in air:
$n_{air} = n_{O2}$ x 100/21 = 376,78 kmol;
$V_{air} = n_{Air}$ x 22.414 = 8.445 Nm^3

1.31. Ozone concentration

The ozone concentration at a monitoring site is measured as 0.11 ppm, at 25°C and 1 atm. What is the concentration (in µg/m^3) at 25° and 1 atm? (MW of Ozone is 48)

1.31.1 Solution

$$C_{mass} = \frac{M_P}{V_t} = \frac{C_{ppm} * MW_P}{R * T/P}$$

Where:
Cmass= mass concentration, µg/m^3
Cppm= volume or molar concentration, ppm
Mp= mass of pollutant gas, µg
MWp= molecular weight of pollutant gas, g/gmol
P = preassure, Pa
R= 8.314 Pa*m3/gmol*K

Therefore, the results is 215.9 µg/m^3.

1.32. Adiabatic saturation of air

Case A
Unsaturated air entering a wet scrubber has: t1 (dbtemp)= 20°C; RH, relative humidity = 50% (v/v). Calculate: h1, h2 (sat.), twetbulb , x1 , and x2.

Case B
Unsaturated air entering a wet scrubber has: t1 (dbtemp)= 90°C; RH, relative humidity = 50% (v/v).. Calculate: h1, h2 (sat.), twetbulb , x1 , and x2.
Case C
Unsaturated air entering a wet scrubber has: t1 (dbtemp)= 110°C; H, absolute humidity = 1 g/g. Calculate: h1, h2 (sat.), twetbulb , x1 , and x2.

1.32.1 Solution

h1=1.005 * t1 + x1(1.84 t1+2501)
t1=20°C
x1=mH2O/mdry air=18*pH2O/29*(p-pH2O)
Where:
pH2O = partial pressure of water vapor
p = total gas pressure =1 atm= 98070 Pa

The partial preassure of water vapour can be estimated by the information of RH=100*(pH2O/pv,H2O)
The pv,H2O at 20°C is tabulated and equal to 2265 Pa (see next slide), therefore pH2O is equal to 1132 Pa.
x1=(18*1132)/(29*(98070-1132))
x1= 0,0073 kg water vapor /kg dry air
h1= 38.7 kJ/kg; h2= 38.7 kJ/kg;
twb= 14°C (from psychrometric calculator);
x2=0.0098 kgwater vapor/kgdry air

H2O abs for saturation: 0.0098 – 0.0073= 2.5 g w /kg dry air
ΔT air flow = 14 – 20 = - 6°C

1.33. Units

Considering the unit concentration “ppm”, which parameters could affect it?
a) Temperature
b) Preassure
c) Temperature and preassure
d) Neither of them

1.33.1 Solution

d) Neither of them

1.34. Mass concentration conversion

From actual conditions (50 °C, 1 atm) to STP ones, how does the conc. (mg/m3) change?
a) Higher
b) Lower
c) Equal
d) It depends on the preassure

1.34.1 Solution

a) Higher

1.35. Avogadro Rule’s

Which is the volume of 10 moles of NO2 at T=0°C (273 K) and P=1 atm (101,3 kPa)?
a) I can’t estimate it
b) 0.22 m^3

c) 1 l
d) 8.314 m^3

1.35.1 Solution

b) 0.22 m^3

1.36. Universal gas constant

Which is the value for the universal gas constant (R) in m3 Pa K−1 mol−1?
a) 8.314×10−6
b) 83.144
c) 8.3141
d) 8.205×10−5

1.36.1 Solution

c) 8.3141

1.37. Standard reference condition

What do standard conditions mean?
a) T=0°C and p= 1 atm
b) T= 293.15 and p= 1 atm
c) T=273.15 K and p=1 bar
d) T= 20°C and p= 1 bar

1.37.1 Solution

c) T=273 K and p=1 bar

1.38. Le Chatelier's principle – effect adding an inert gas

What does it happen to the equilibrium constant of a reaction if an inert gas is introduced at constant volume?
a) the equilibrium constant decreases
b) the equilibrium constant increases
c) the equilibrium constant does not result in a shift

1.38.1 Solution

The answer is C)
EFFECT ADDING AN INERT GAS. Adding an inert gas into a gas-phase equilibrium at constant volume does not result in a shift. This is because the addition of a non-reactive gas does not change the equilibrium equation, as the inert gas appears on both sides of the chemical reaction equation

1.39. Density of air

Does it weigh more dry air or moist air?

a) Dry air
b) Moist air
c) They are equal

1.39.1 Solution

The answer is a)
MW of dry air= 0.79*28+0,21*32~ 29

MW of H_2O= 18

1.40. Density of air

Which is the density of a landfill gas with a composition (% by volume, dry) of 50% of CH_4 and 40 % of CO_2, 2% of O_2 and 8% of N_2 at 0°C and 1 atm.
Assume that the density of dry air is 1.29 grams per liter at 0°C and 1 atm

1.40.1 Solution

Density=mass/volume
Applying the ideal gas law:
Density= (P*MW)/(R*T)
Therefore for the same condition
Density gas_1/ Density gas_2= MW_1/MW_2
MW landfill gas= 28.48
Density landfill gas = 1.29 * 28.48/29 = 1.26 kg/m3

1.41. Solubility

Which is the most soluble gas?
a) CO
b) CO_2
c) SO_2
d) SO_3
e) NO
f) NO_2
g) NH_3
h) HCl

1.41.1 Solution

Using the values of H reported in Sander (Sander, 2015)

- NO → H= $2.3*10^{-5}$ Mol/m^3*Pa
- CO → H= $7.9*10^{-5}$ Mol/m^3*Pa
- NO_2 → H= $4.0*10^{-4}$ Mol/m^3*Pa
- CO_2 → H= $4.5*10^{-4}$ Mol/m^3*Pa
- SO_2 → H= $4.0*10^{-1}$ Mol/m^3*Pa
- NH_3 → H= $7.4*10^{-1}$ Mol/m^3*Pa
- HCl → H= $1.5*10^{1}$ Mol/m^3*Pa
- SO_3 → H= ∞ Mol/m^3*Pa

Analysing the data, the most soluble gas is SO_3, then HCl.

1.42. Chemical reactions in atmosphere

If both NH_3 and SO_2 were emitted at the same place what products do you expect from the direct reaction?
Write also the chemical reaction.

1.42.1 Solution

If both NH_3 and SO_2 were emitted at the same place what products do you expect from the direct reaction? **$(NH_4)_2SO_3$**
Write also the chemical reaction: **$2 NH_3 + SO_2 + H_2O$** (+ O_2) = **$(NH_4)_2SO_3$** .
Also $(NH_4)_2SO_4$ (+ bisulphite and bisulphate) **[water vapour and O_2 are always available in the troposphere!] .**
Under dry atmospheric conditions, solid salts like those above strongly contribute to the production of fine secondary air dust, particularly $PM_{2.5}$. (under wet atmospheric conditions these salts are easily removed being soluble in water)

In Italy, in the year 2010, 419 kton of NH_3 and 475 kton of SO_2 have been emitted.

1.43. Henry law: partial pressure of O_2

What is the partial pressure of O_2, p_{O2}, if the total pressure, P, of air is 1.0 atmosphere and the O_2 content is 21% by volume?

1.43.1 Solution

$x_i = V_i\% = 21/100 = 0.21$
The partial pressure of O_2 is then: $p_i = x_i \cdot P = 0.21 \times 1.0 = 0.21$ atm

1.44. Henry law: concentration of CO_2 in a drop of rain

What is the concentration of CO_2 in a drop of rain in equilibrium with the atmosphere *(T= 25°C; P=1.0 atm; CO_2 = 400 ppm (v,v); $K_H = 0.0338$ mol L^{-1} atm^{-1}; MW=44)?*

1.44.1 Solution

Partial pressure: $P_{CO2} = x_{CO2} \cdot P = 400 \cdot 10^{-6} \cdot 1{,}0 = 4.0 \cdot 10^{-4}$ atm
Henry: $K_H = c_{CO2}/P_{CO2}$
$c_{CO2} = K_H P_{CO2} = (0.0338 \text{ mol } L^{-1} \text{ atm}^{-1})\ (4.0 \cdot 10^{-4} \text{ atm})$
$c_{CO2} = 13.5 \times 10^{-6}$ mol L^{-1} = 13.5 µM
$c_{CO2} = 44 \cdot 13.5 = 0.6$ mg/L *(= 0.6 g/m^3)*

1.45. Henry law: formaldehyde

An industrial gas flow contains HCHO (methanal; Formaldehyde). The ELV is 20 mg/Nm^3. Convert it to ppm and calculate its partial pressure *$K_{H(H2CO,hydr.)} = 6.3 \times 10^3$ M/atm. MW =30.* Calculate the aqueous methanal concentration in equilibrium.

1.45.1 Solution

A) Gas concentration
n_{HCHO} = 20 mg/Nm^3/30 g/mol = 0.66 mmol/Nm^3 ;
V of 1 mmol of gas = 22.414 Ncm^3;
[HCHO]= 0.66 x 22.414 = 15 ppm

B) Partial pressure
$P_i = x_i \cdot P_{tot} = 15 \cdot 10^{-6}$ ppm $\times 1.0$ atm $= 1.5 \cdot 10^{-5}$ atm

C) Liquid concentration
$C_i = K_H \times P_i = 6.3 \times 10^3 \times 1.5 \cdot 10^{-5} = 0.0945$ M

2. REGULATIONS

2.1. Dust emissions

Let's start with the discussion of a small industrial plant with a single chimney emitting to the atmosphere.
The measured waste gas flow emitted from a stack is 2000 m^3/h. The measured concentration of dust = 145 mg/m^3.
The temperature and pressure of the emitted air are T = 24 °C and p = 0.99 atm.

LET'S CONCENTRATE ON THE EMISSION OF DUST.

A. What must be done?
B. Calculate the mass flow of the pollutant
C. Are there any limits or rules that must be complied?
D. Does the plant respect the limits?

Figure. POLLUTING PLUME EMITTED FROM A TALL STACK- Fumigating plume

2.1.1 Solution

Question A)

1st - Use materials or manifacturing cycles producing less dust [choose this whenever it is possible, since it is Pollution Prevention!]
2nd - REDUCE THE DUST CONTENT OF THE EMITTED PLUME! (through, e.g., efficient dust removal techniques)
3rd - RISE THE PLUME HEIGHT

Question B)

f_{dust} = 2000 x 145 = 290 g/h (= 0.3 kg/h)

Question C)

YES, Italy has set general ELVs for emissions OF dust AND FOR MANY OTHER POLLUTANTS (Allegato I -Valori di emissione e prescrizioni, Parte I e Parte II della Parte quinta del D.Lgs. 152/2006 e s.m.i.)
There are NOT EU general limits for emissions of dust or other pollutants!

The rule is (from D.Lgs. 152/2006, Allegato I alla parte quinta, parte II):
«5. Polveri totali.
Il valore di emissione è pari a:

- 50 mg/Nm^3 se il flusso di massa è pari o superiore a 0,5 kg/h; (FDUST ≥ 0.5 kg/h)
- 150 mg/Nm^3 se il flusso di massa è pari o superiore alla soglia di rilevanza corrispondente a 0,1 kg/h ed è inferiore a 0,5 kg/h.» (≤ 0.1 FDUST < 0.5 kg/h)»

Comment: These limits are rather old. They have been set in 1990, about 30 years ago.
CURRENTLY APPLIED LIMITS ARE ABOUT 1/10-th OF THESE VALUES!!

The limits are expressed as 50 and 150 mg/Nm3, this means that the ELVs refer to normal conditions, i.e. 0 °C and P = 1.0 atm!).
ELVs ALWAYS – EU AND ITALY - ARE EXPRESSED AS NORMAL CONCENTRATIONS.

Question D)

hence ELV for DUST is: 150 mg/Nm3
The measured concentration (145 mg/m3) should be corrected for the reference conditions.
Consider the actual conditions: T = 24 °C; p = 0.99 atm.
Then we apply the general gas law: PV/T = P0V0/T0
V0 = P/P0 x T0/T x V = 1/0.99 x 273/297 x V = 1.01 x 0.92 x V = 0,93 V
1.0 m^3 of waste air corresponds to a volume of 0.93 Nm^3
And c_{DUST} = 145 mg/m3 = 145/0.93 = 145 x 1.077 = 156 mg/Nm3.
The limit is not respected.

Please note that if the waste gas flow emitted from a stack were 4000 m^3/h, and the measured concentration of dust were 145 mg/m3.
The mass flow of dust, would be: 4000 x 145 = 580 g/h (= 0.6 kg/h) with ELV = 50 mg/Nm3!
AT THIS POINT, I MUST SAY THAT VERY SELDOM THE COMPOTENT AUTHORITY PERMITS ALLOW SUCH HIGH LIMITS!!
TYPICALLY ELVs FOR DUST EMISSIONS ARE IN THE RANGE OF 10 – 20 mg/Nm3 (dry conditions)… or lower!

For example, the Italian procedure AUA (DPR 59/2013 - Autorizzazione Unica Ambientale) for small-medium facilities NOT UNDER AIA-IPPC!) set a maximum ELV for dust equal to 10 mg/Nm3 (but values of 3 mg/Nm3 are required for many activities).

3. DUST REMOVAL: GENERAL CONCEPTS

3.1. Terminal settling velocity

Question a)
Calculate the terminal velocity for a 10 µm particle in air.
Data:
density (ρ_g)=1.2 x 10^{-3} g cm^{-3};
viscosity (µ) = 1.8 x 10^{-4} g $cm^{-1}s^{-1}$;
particle density (ρ_p)=**1.0** g cm^{-3};
T=20°C.
Question b)
Calculate the terminal velocity for a larger (100 µm) and heavier particle in air.
Data:
density (ρ_g)= =1.2 x 10^{-3} g cm^{-3};
viscosity (µ) = 1.8 x 10^{-4} g $cm^{-1}s^{-1}$;
particle density (ρ_p)= =**2.0** g cm^{-3};
T=20°C.
Question c)
Calculate the terminal velocity for a 10 µm particle in air, but in a circular gas flow with velocity v_c=18.29 m/s and radius r=0.3048 m.
Data (the same of question a):
density (ρ_g)=1.2 x 10^{-3} g cm^{-3};
viscosity (µ) = 1.8 x 10^{-4} g $cm^{-1}s^{-1}$;
particle density (ρ_p)=**1.0** g cm^{-3};
T=20°C.
Question d)
Which APC strategies will you suggest to remove dust?

3.1.1 Solution

Question a)
We will first calculate the K value:

$$K = d_p \left(\frac{g\ \rho_p \rho_g}{\mu^2} \right)^{0.33}$$

$$K = 10x10^{-4}\,cm \left(\frac{980 \frac{cm}{s^2}\ x\,1.0 \frac{g}{cm^3}\ x1.2x10^{-3} \frac{g}{cm^3}}{\left(1.8x10^{-4}\right)^2 g^2 cm^{-2} s^{-2}} \right)^{0.33} \approx 0.3$$

Thus, this is in the laminar flow region.
Note that for more viscous gases, the K value would be much smaller. Thus, more viscous gases have larger laminar flow regions (i.e. flow is less likely to be turbulent) than less viscous gases. Assuming Cu=1.0, the terminal velocity for this particle is:

$$v_t = \frac{Cu\, d_p^2 \rho_p\ g}{18\mu} = \frac{1 \cdot 0.001^2\,[cm]^2\, 1 \left[\frac{g}{cm^3}\right]\ 980\ \left[\frac{cm}{s^2}\right]}{18\,x1.8x10^{-4}\left[\frac{g}{cmxs}\right]} = 0.3\frac{cm}{s}$$

Despite being a “coarse” particle in ambient air, this particle is relatively small for being removed by gravity-based settling equipments.

Question b)
K value:

$$K = 100x10^{-4}\,\text{cm}\left(\frac{980\,\frac{\text{cm}}{\text{s}^2}\ \text{x}\ 2.0\,\frac{\text{g}}{\text{cm}^3}\ \text{x}1.2\text{x}10^{-3}\,\frac{\text{g}}{\text{cm}^3}}{\left(1.8\text{x}10^{-4}\right)^2\ \text{g}^2\text{cm}^{-2}\text{s}^{-2}}\right)^{0.33} \approx 3.9$$

This is in the transition flow regime. A different equation for the terminal velocity will be used:

$$\text{v}_t = \frac{0.153\text{d}_p^{1.14}\rho_p^{0.71}\ \text{g}^{0.71}}{\mu^{0.43}\ \rho_g^{0.29}} = \frac{0.153(0.01)^{1.14}(2)^{0.71}\ 980^{0.71}}{(0.00018)^{0.43}\ 0.0012^{0.29}} = 50\,\frac{\text{cm}}{\text{s}}$$

Obviously, with this greater terminal velocity, the denser and larger particle would be much more amenable to gravitational collection equipment.

Question c)

$$\text{v}_\text{t} = \frac{\text{d}_\text{p}^2\,\rho_\text{p}\ \text{v}_\text{c}^2}{18\mu\text{r}} = \frac{(10\text{x}10^{-6})^2[\text{m}^2]1000\ \left[\frac{\text{kg}}{\text{m}^3}\right](18.29)^2\left[\frac{\text{m}^2}{\text{s}^2}\right]}{18\cdot 1.8\text{x}10^{-5}\left[\frac{\text{kg}}{\text{ms}}\right]0.3048[\text{m}]} = 0.33\left[\frac{\text{m}}{\text{s}}\right] = 33\left[\frac{\text{cm}}{\text{s}}\right]$$

This value is 100 times as large as the previous value (see question a) indicating that much greater settling velocities can be obtained by applying centrifugal forces.

3.2. Centrifugal force vs gravity force

Question a)

Calculate the ratio of centrifugal force to the gravity force acting on a particle traveling in a gas stream with velocity 18 m/s and radius r=0.3048 m.

Question b)

Calculate the ratio of centrifugal force to the buoyance force acting on a particle traveling in a gas stream with velocity 18 m/s and radius r=0.3048 m.

Density gas: 1.2 kg/m^3

Density particulate =2000 kg/m^3

3.2.1 Solution

Question a)

Gravity force:

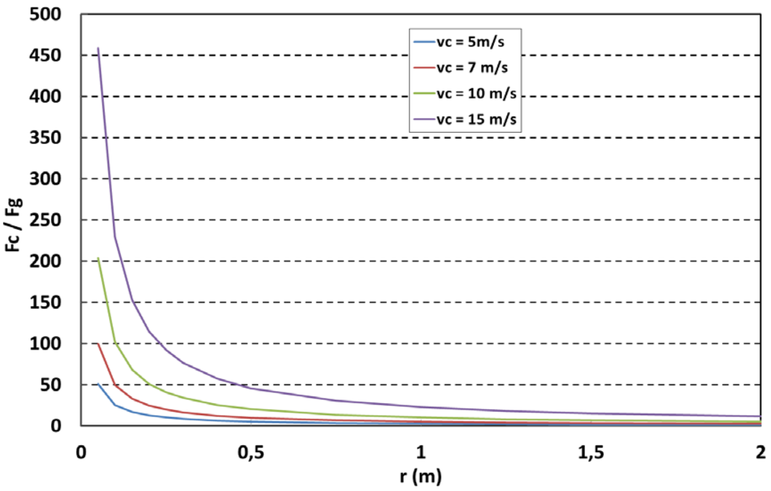
$$\text{F}_G = \text{m}\ g$$

Centrifugal force:

$$\text{F}_\text{c} = \text{m}\,\frac{\text{v}_\text{c}^2}{\text{r}}$$

$$\frac{\text{F}_\text{c}}{\text{F}_\text{G}} = \frac{\text{m}\,\frac{\text{v}^2{}_\text{c}}{\text{r}}}{\text{mg}} = \frac{\text{v}^2{}_\text{c}}{\text{rg}} =$$

$$= \frac{(18)^2\left[\frac{\text{m}^2}{\text{s}^2}\right]}{0.3048[\text{m}]9.81\left[\frac{\text{m}}{\text{s}^2}\right]} = 108.5[-]$$



At even modest velocity and common radii, the centrifugal forces acting on a particle can be 2 orders of magnitude larger than the gravity forces.

For this reason centrifugal separators are more useful than gravity settlers.

Question b)

Buoyance force:

$$F_B = m_F g = \rho_F V_F g = \pi \frac{d_p^3}{6} \rho_F g$$

Centrifugal force:

$$F_c = m \frac{v_c^2}{r}$$

$$\frac{F_c}{F_B} = \frac{m \frac{v^2{}_c}{r}}{\pi \frac{d_p^3}{6} \rho_F g} = \frac{\pi \frac{d_p^3}{6} \rho_P \frac{v^2{}_c}{r}}{\pi \frac{d_p^3}{6} \rho_F g} = \frac{\rho_P \, v^2{}_c}{\rho_F g \cdot r}$$

$$= \frac{(18)^2 \cdot 2000}{1.2 \cdot 9.81 \cdot 0.3048} \approx 180000$$

3.3. Penetration efficiency

Dusty air at a fertilizer plant flows through a 73% efficient cyclone and then through an ESP. The inlet air to the cyclone has a dust loading of 80 g/m^3.

In order to meet a standard of 98.5% collections efficiency for the fertilizier plant as a whole, what is allowable concentration of dust (in g/m^3) in the air that exits from the ESP?

Calculate the required collection efficiency for just the ESP in the above problem.

3.3.1 Solution

Overall penetration

$$P_t = 1 - \eta$$

$$P_{t,tot} = \prod_{i=1}^{n} P_{t,i}$$

Concentration out=80*(1-0.985) = 1.2 g/m^3

The efficiency of ESP is 94.5%

3.4. PM size distribution

The following table provides the PM size distribution by mass and the collection efficiency for a proposed control device as a function of particle size.
Estimate the overall collection efficiency of the control device on this PM.

Size range (µm)	mass fraction	Efficiency %
0-6	10	20,00
6-16	30	50,00
16-30	40	83,00
>30	20	100,00

3.4.1 Solution

The solution is reported in the following table:

Size range (µm)	mass fraction	Efficiency %	% collected
0-6	10	20,00	2,00
6-16	30	50,00	15,00
16-30	40	83,00	33,20
>30	20	100,00	20,00
	100		**70,20**

4. GRAVITY SETTLING CHAMBERS

4.1. Designing a settling chamber

Calculate the minimum size of the particle that will be removed with 100 percent efficiency from a settling chamber under the following conditions:

- Viscosity of air is 2.1*10-5 kg/m*s
- Horizontal velocity is 0.3 m/s;
- Temperature is 77°C;
- Particulate density is 2000 kg/m3
- Chamber: lenght is 7.5 m; height is 1.5 m.

4.1.1 Solution

$$d_{p,min} = \sqrt{\frac{18 \cdot \mu \cdot v_H \cdot H}{g \cdot L \cdot \rho_p}}$$

dp,min=34.02 µm
With a safety factor of 2
dp,min*=48,1 µm

4.2. Characteristics of gravity settling chambers: insert the correct word

Insert the correct word in the following sentences:

Q1. Gravity settling chamber removes _____________ particles.
Q2. In gravity settling chamber, the gas velocity of less than _______ m/s will produce good results.
Q3. If trays are used in settling chamber efficiency _______________.

4.2.1 Solution

Q1. Gravity settling chamber removes **large** particles.
Q2. In gravity settling chamber, the gas velocity of less than **0.3** m/s will produce good results.
Q3. If trays are used in settling chamber efficiency **increases**.

5. CYCLONES

5.1. Cyclone design

Design a conventional cyclone to function as a precleaner on a gas stream that flows at 120 m3/min. The cyclone must achieve a minimum overall efficiency of 70% for the following particulate distribution, with a maximum allowable ΔP of 3000 Pa.

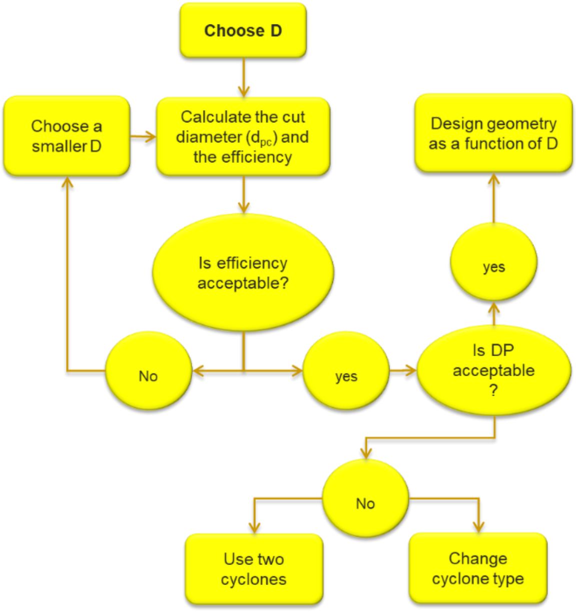
The particulate density is 1500 kg/m^3, the gas density is 1.0 kg/m3 and the gas viscosity is 0,07 kg/m-hr. Specify your final choice of body diameter, overall cyclone efficiency, inlet gas velocity and pressure drop (assume K=14).

Size range (μm)	mass percent in size range
0-2	2
2-4	18
4-10	30
10-20	30
20-40	15
40-100	4
>100	1
	100

5.1.1 Solution

A trial-and-error procedure can be used (see figure):

- First choose a body diameter;
- Calculate the corresponding dpc and efficiency.
- If efficiency is too low, a smaller body diameter must be chosen and the procedure iterate.
- If the efficiency is acceptable, the pressure drop must be checked.
- If DP is too high, we can either choose a different type of cyclone or split the flow gas between two cyclones in parallel.



- Diameter = 0,8 m
- Flue gas inlet velocity (uin) = (120/0.4*0.2)/60=25 m/s. The velocity is in the range of optimum design conditions 15 m/s - 30 m/s
- Estimation of the Number of effective turns (Ne)= 6
- Estimation of the cut diameter (dpc)=4.98 μm

With this data we can estimate the efficiency for each size range $E(d_{p,i})$:

$$E(d_{p,i}) = \eta(d_{p,i}) = \frac{1}{1 + (\frac{d_{pc}}{d_{p,i}})^2}$$

Therefore the total efficiency is:

Size range (µm)	mass percent in size range	dp av	dp/dpc	Efficiency E(dp,i)	% collected
0-2	2	1	0,20	0,04	0,08
2-4	18	3	0,60	0,27	4,79
4-10	30	7	1,41	0,66	19,92
10-20	30	15	3,01	0,90	27,02
20-40	15	30	6,03	0,97	14,60
40-100	4	70	14,06	0,99	3,98
>100	1	100	20,09	1,00	1,00
	100				**71,39**

- Total Efficiency= 71,39%. It is verified the requirement of the exercise.

The preassure drop is estimated equal to 22,3 cm H_20.

5.2. Multicyclones

Explain theoretically why multicyclones configuration has a better efficiency of classical configuration?

5.2.1 Solution

Particle orbit radius $r_{p:}$

$F_C = F_A \rightarrow r_p = \rho_p d_p^2 v_C^2/(18\ \mu\ u_r)$

v_c = tangential velocity; u_r = radial velocity

Capture efficiency increase with rp: smaller cyclones more efficient →multicyclone configurations

5.3. Advantages of cyclones

Which of the following sentences are true advantages of cyclones application?

- low investment costs
- low erosion and/or clogging operating risks
- removal efficiency indipendent to dust granulometry
- Can handle liquid mists or dry materials
- contained space requirements
- high whole removal efficiency

5.3.1 Solution

Advantages

- low investment and operating costs (contained pressure drops)
- Ability to operate at high temperature
- simpler maintenance (no moving equipment or ancillary devices, simple design)
- Can handle liquid mists or dry materials
- dry captured particulates discharge
- contained space requirements

Drawbacks

- low capture efficiencies for finer particles
- erosion and/or clogging operating risks

5.4. Efficiency of cyclones

A gas-particle separation device is tested and gives the results shown in the table below:

Sinze range	0-10	10-20	20-30	30-40	40-50
Range mean (µm)	5	15	25	35	45
Feed mass (kg)	45	69	120	45	21
Coarse product mass (Kg)	1.35	19.32	99.0	44.33	21.0

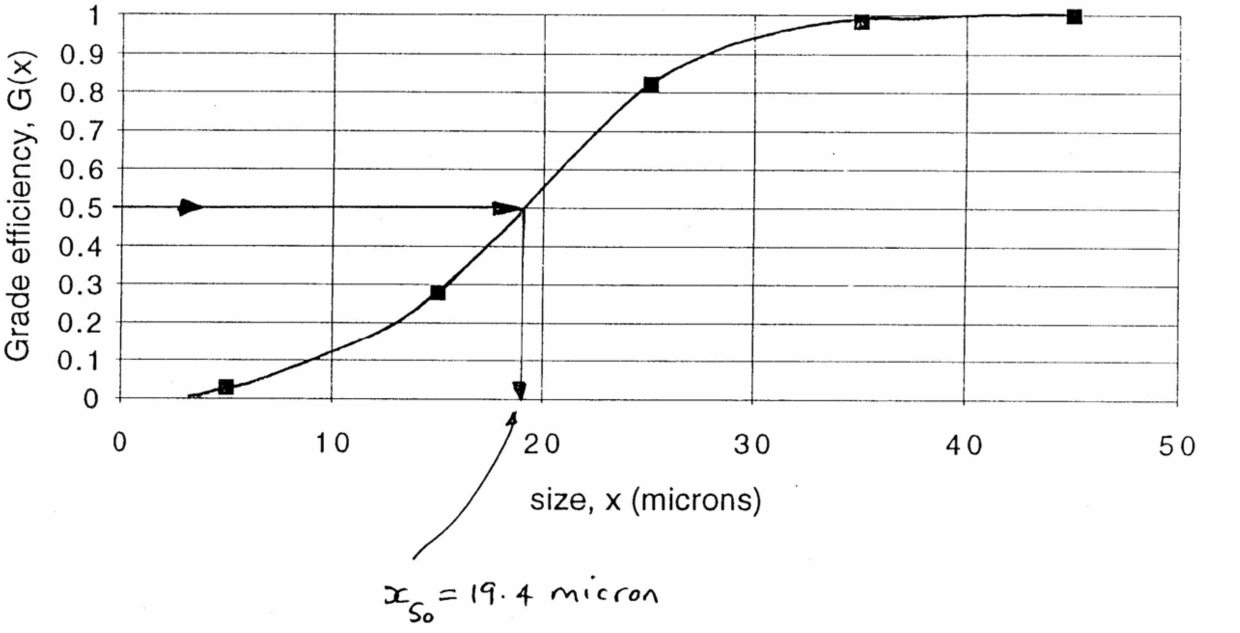
a) Find the total efficiency of the device.
b) Produce a plot of the grade efficiency for this device and determine the equiprobable cut size.

5.4.1 Solution

(a) From the test results:
Mass of feed (M), M = 45 + 69 + 120 + 45 + 21 = 300 grams.
Mass of coarse product (Mc), Mc = 1.35 + 19.32 + 99 + 44.33 + 21 = 185 grams.
Therefore, the total efficiency, ET=Mc/M=0.617 (or 61.7 %)
(b) In this case, G(x) may be obtained directly from the results table as $G(x)=Mc_x/M_x$
For example, for the size range 0-10 µm, Gx()=1.35/45=0.3. For the remaining size ranges:

Sinze range	0-10	10-20	20-30	30-40	40-50
G(x)	0.03	0.28	0.825	0.985	1.000

Plotting this data gives x50 = 19.4 µm, as may be seen from Solution-Manual-Figure 9.1.1



6. FABRIC FILTERS

6.1. Estimation number of bags

A fabric filter is treating 50.000 Nm^3/h with an average air-to-cloth ratio of 1.2 m/min. The bags are 0.15 m in diameter and 3.6 m long. Estimate the number of bags in the baghouse.

6.1.1 Solution

Vf=Q/A
The cloth area is 50.000/(1.2*60)= 694,4 m^2
The filtration area of one single bag is 0.15*3.14*3.6=1.7 m^2
Therefore the number of bags is (694.4/1.7)=410

6.2. Sizing Fabric Filters

Calculate the number of bags required for an 8-compartment pulse-jet baghouse with the following process information and bag dimensions:
process gas exhaust rate (Q) = 45 (m^3/s) (=162000 m3/h)
Air (flow)-to-cloth ratio (A/C)= filtration velocity (vf)= 0.02 (m3/s)/m2 = 0.02 m/s (1.2 m/min)
Bag size
bag diameter: 0.15 m *(6")*
bag height: 3.6 m
Bag spacing: 5 cm
Finally, calculate the can velocity in the baghouse

6.2.1 Solution

A. Calculate the total cloth area

$$A_c = \frac{45 m^3/\sec}{0.02 m/\sec} = 2{,}250 m^2$$

B. Determine one single bag filtration area
Bag filtration area, $A_b = \pi$ d h
Where:
A_b=filtration area of one single bag (m^2)
d=0.15 m, bag diameter
h=3.6 m, bag height

A_b = 3.14 x 0.15 m x 3.6 m = 1.70 m^2

C. Calculate the number of bags in a baghouse

$$number\_of\_bags = \frac{A_c}{A_b} = \frac{2{,}250 m^2}{1.70 m^2} = 1{,}327 bags$$

There will be an even number of bags in each of the 8 compartment, so the bags number (1327) should be rounded to the next highest multiple of 8 (i.e. 1,328). Thus, there will be 166 bags (1,328/8) in each compartment.

D. Calculate the can velocity in the baghouse
v_{can} = Q/(A-B) (m/s)
Q = Actual gas flow (m^3/s)
A = Area of the tubesheet: rectangular base width x length (m^2)
B = Area of the bottom of the bags: (n° of bags) x [π x (out diam)^2/4] (m^2)
The net flow area (A-B) is determined by subtracting the total axial cross-sectional area of the bag filters from the baghouse chamber's total cross-sectional area.
Number of bags = 1328

Bottom area of 1 bag = π d2 /4 = 3.14 x 0.152 /4= 0.018 m^2
B = Total area of bottom bags = π d2/4 x 1328 = 23 m^2
a = bag diameter + bag spacing = 15 + 5 = 20 cm = 0.2 m
A = Tube sheet area = a^2 x 1328 = (0.15+0.05)2 x 1328 = 53 m^2
vcan = Q/(A-B) = 45 /(A-B) = 45 / 30 = 1.5 m/s = 90 m/min
Notes:
BHs should be designed for can velocities between 80 m/min and 90 m/min.
(A-B) = net flow (or free) area = 53 – 23 = 30 m2; % free area = (30 / 53) x 100 = 57%

6.3. Pressure drop in a BH

Calculate the design pressure drop in a baghouse after 70 minutes of operation with dust loading (L)=5.0 g/m^3 and superficial filtering velocity (v)=0.9 m/min.
Base the estimate on the test carried out on a clean fabric at the same operating conditions.

Table 1. Test data at planned operating conditions:

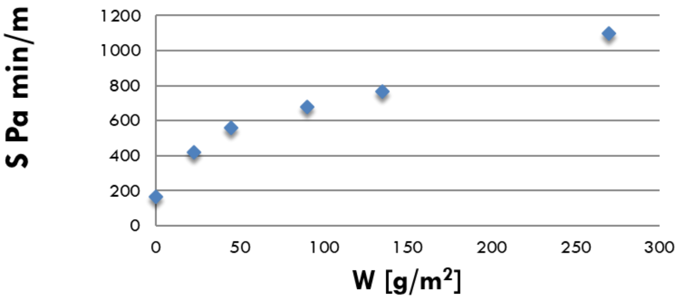
Time [min]	DP [Pa]
0	150
5	380
10	505
20	610
30	690
60	990

6.3.1 Solution

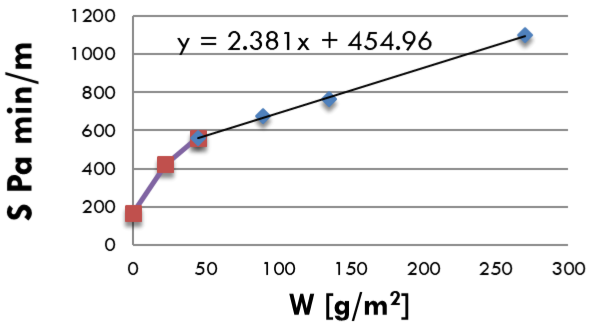
We'll use the experimental data for plotting the Filter Drag Curve S=S(W). At each t value, we'll calculate S and W.

$$S = \frac{\Delta P}{v}$$
$$W = Lvt$$

S	W
Pa min/m	g/m^2
167	0
422	22.5
561	45
678	90
767	135
1100	270



The curve has a non linear initial portion, to be ignored in obtaining the slope and intercept
From a linear least square fit of the last four data points, we can estimate the values of the constants Ke and Ks.



$$K_e = \text{extrapolated clean cloth filter drag} = 455\left[\frac{\text{Pa min}}{\text{m}}\right]$$

$$K_s = \text{slope constant for the particulate dust, gas and fabric involved} = 2.381\left[\frac{\text{Pa min m}}{\text{g}}\right]$$

Knowing the coefficients of the filter drag model, we can now calculate the Filter Drag S and thus predict the design pressure drop:

$$W = 5\frac{\text{g}}{\text{m}^3}\text{x}0.9\frac{\text{m}}{\text{min}}\text{x}70\text{min} = 315\frac{\text{g}}{\text{m}^2}$$

$$S = K_e + K_s W$$

$$\text{S} = 2.381 \cdot 315 + 455 = 1205 \text{ Pa m/min}$$

$$S = \frac{\Delta P}{v}$$

ΔP=S·*v=1085 Pa =11.06 cmH20

7. ELECTROSTATIC PRECIPITATORS

7.1. Estimate the effective drif velocity

An ESP is treating the flue gas from a coal combustion unit and achieving a 98% PM removal efficiency. They start burning a new coal and the efficiency drops to 93%, but the gas flow rate has remained exactly the same. Estimate the ratio of the new effective drift velocity (w_{new}) to the old one (w_{old})

7.1.1 Solution

Applying the relationship:
weff = - ln(1-ET)·Q/A,
we obtain a ratio $w_{eff,\ new}$/ $w_{eff,\ old}$=0,68

7.2. Ratio between driving force and resisting force

Compare the influence of particulate diameter (dp) on the ratio of driving force (external force) and resisting force (drag force) for an ESP and a cyclone unit.
For the drag force you can use the Stoke's law

7.2.1 Solution

Drag force for an ESP and a cyclone unit → $F_A = 3p\mu_f \mathbf{d_p} v$
External force for an ESP →$F_E = 3p\mathbf{d_p}^{\mathbf{2}} K\ E\ D/(D+2)\ E$
External force for a Cyclone → $F_E = \rho_p(\ \pi \mathbf{d_p}^{\mathbf{3}}/6)v^2/r$
Therefore
The ratio driving force/resisting force for an ESP is proportional to the diameter
The ratio driving force/resisting force for an Cyclone is proportional to the diameter squared

7.3. Active plate area and Number of plates

An ESP treating 10450 m^3/min of air must reach an efficiency of 98%.
Effective drift velocity we = 6 m/min
Plates height H= 6 m;
Plates lenght L= 3 m;
Number of mechanical fields Ns=2.
Calculate:

a) the Active Plate Area
b) the number of plates required
c) estimate the number of ducts (Nd) assuming a velocity of flue gas of 70 m/min and a channel width of 0.25 m
d) verify the estimated area with the one derived from geometry considerations only

7.3.1 Solution

a) Active Plate Area
Since : $\eta = 1\text{-e}^{\frac{-wA}{Q}}$
A=6813 m^2

b) Number of plates required
Moreover, since:
A=Ap (n-1) Ns=Ap (N-Ns)
Where:
Ap= two-sided plate area (=2HLp)
n = number of plates in parallel across the width of the ESP
Ns= number of sections in direction of flow range of values: 2-6)

N= total number of plates in the ESP
N= 192 plates

c) Number of ducts
Nd=Q/(u*b*H) =100

d) Collection Area Derived From Geometry Considerations only

Aa=2*H*Lp*Ns*Nd= 7165 m^2
It is verified.

7.4. Migration velocity in ESP

Does the migration velocity in ESP depend on the flue gas velocity? Which is the consequence?

7.4.1 Solution

Migration velocity not dependent on flue gas velocity: no need to increase gas velocity for enhancing particle collection velocity, thus decreasing gas residence time → ESP large enough to obtain adequate residence time without affecting wd.

7.5. Electrostatic precipitator: complete with the correct word

1. In an electrostatic precipitator, the ____________________ electrode is normally a small-diameter metal wire or a rigid frame containing wires.

2. The charged particles migrate to the ____________________ ____________________.

3. In a single-stage, high-voltage ESP, the applied voltage is increased until it produces a(an)
    a. Extremely high alternating current for particle charging
    b. Corona discharge, which can be seen as a blue glow around the discharge electrode
    c. Corona spark that occurs at the collection electrode

4. True or False? Particles are usually charged by negative gas ions that are migrating toward the collection electrode.

5. True or False? Large particles move more slowly towards the collection plate than small particles.

6. The average sparkover rate (in sparks per minute) for optimum precipitator operation is between:
    a. 1 - 25
    b. 50 - 100
    c. 100 - 150
    d. 500 - 1,000

7. As dust particles reach the grounded collection electrode, their charge is:
    a. Immediately transferred to the collection plate
    b. Slowly leaked to the grounded collection electrode
    c. Cancelled out by the strong electric field

8. Particles are held onto the collection plates by:
    a. A strong electric force field
    b. A high-voltage, pulsating, direct current
    c. Intermolecular cohesive and adhesive forces
    d. Electric sponsors

9. Dust that has accumulated on collection electrodes can be removed either by ____________________ ____________________ or a process called ____________________.

10. True or False? During the rapping process, the voltage is turned down to about 50% of the normal operating voltage to allow the rapped particles to fall freely into the hopper.

11. ____________________ electrostatic precipitators are used for removing particulate matter from flue gas that usually has a temperature range of 320 to 420° C (608 to 790° F).

12. In a boiler, hot-side ESPs are located ____________________ air preheaters, whereas cold-side ESPs are located ____________________ air preheaters.

  a. In front of, behind
  b. Behind, in front of

13. True or False? Wet electrostatic precipitators are used when collecting dust that is sticky or has high resistivity.

14. ____________________ ESPs are units where particle charging occurs in the first stage, followed by collection in the second stage.

7.5.1 Solution

1. Discharge
In an electrostatic precipitator, the discharge electrode is normally a small-diameter metal wire or a rigid frame containing wires.

2. Collection electrode
The charged particles migrate to the collection electrode.

3. b. Corona discharge, which can be seen as a blue glow around the discharge electrode
In a single-stage, high-voltage ESP, the applied voltage is increased until it produces a corona discharge, which can be seen as a blue glow around the discharge electrode.

4. True
Particles are usually charged by negative gas ions that are migrating toward the collection electrode.

5. False
Large particles move faster towards the collection plate than small particles. Large particles have a higher saturation charge than small particles; consequently, large particles are pulled more strongly to the collection plate.

6. b. 50 - 100
The average sparkover rate for optimum precipitator operation is between 50 - 100 sparks per minute.

7. b. Slowly leaked to the grounded collection electrode
As dust particles reach the grounded collection electrode, their charge is slowly leaked to the grounded collection electrode.

8. c. Intermolecular cohesive and adhesive forces
Particles are held onto the collection plates by intermolecular cohesive and adhesive forces.

9. Water sprays
Rapping
Dust that has accumulated on collection electrodes can be removed either by water sprays or a process called rapping.

10. False
During the rapping process, the voltage is NOT turned down. Rapping occurs while the ESP remains on-line.

11. Hot-side
Hot-side electrostatic precipitators are used for removing particulate matter from flue gas that usually has a temperature range of 320 to 420°C (608 to 790°F).

12. a. In front of, behind
In a boiler, hot-side ESPs are located in front of air preheaters, whereas cold-side ESPs are located behind air preheaters. Recall that flue gas is cooled as it passes through the combustion air preheater.

13. True
Wet electrostatic precipitators are used when collecting dust that is sticky or has high resistivity.

14. Two-stage
Two-stage ESPs are units where particle charging occurs in the first stage, followed by collection in the second stage.

7.6. Drift velocity in ESP (wd)

Drift velocity due to an electrostatic force for a 10 µm particle.
A 10 µm particle of a material with a dielectric constant D of 6 (-) reached its equilibrium charge in an ESP at a place where the field strength is 300 kV/m. How many electronic charges has it? What is the value of the drift velocity?
Data:
Permittivity constant K0=8.85*10-12 C/V/m
Gas viscosity µ=1.8*10-5 kg/m/s

7.6.1 Solution

The theoretical saturation charge for a spherical particle is:

$q = 3\pi d^2 K_0 E\ D/(D+2)$
q= 1.87576E-15
Since 1C = 6.24150975·1018e
q= 11707 electrons
The drift velocity is:

$$w_d = \frac{K_0 E^2 d_p}{\mu} \frac{D}{(D+2)}$$

wd= 0.332 m/s
Since the terminal velocity is proportional to the square of E, which in turns is approximately **equal to the wire voltage divided by the wire-to-plate distance**, we should be able to achieve unlimited drift velocities.
The limitation is the **sparking process**.
E= dV/Dx
Where:
Dv is the difference of voltage between collecting electrodes and discharge electrods
dX is the distance between collecting electrode and discharge electrod

7.7. Drift velocity in ESP (wd)

Drift velocity due to an electrostatic force for a 1 µm particle.
A 10 µm particle of a material with a dielectric constant D of 6 (-) reached its equilibrium charge in an ESP at a place where the field strength is 300 kV/m. How many electronic charges has it? What is the value of the drift velocity?
Data:
Permittivity constant K0=8.85*10-12 C/V/m
Gas viscosity µ=1.8*10-5 kg/m/s

7.7.1 Solution

See above for the solution.
Since the charge is proportional to the diameter squared, a 1 mm particle will have electronic charges about 2 orders of magnitudo lower than a 10 mm particle.
q= 1.87576E-17 Coulomb

The drift velocity is:
wd= 0.0331875 m/s
This drift velocity here is relatively low, but it is 5 times higher than terminal velocity computed for the same particle in a cyclone and 1000 times higher than for a gravity settler.

8. GAS ADSORPTION AND DRY TECHNIQUES

8.1. Physical adsorption

True or False? The physical adsorption process is an exothermic process. The forces holding the gas molecules to the solid are easily overcome by the application of heat

True or False? The physical adsorption process is an exothermic process. The forces holding the gas molecules to the solid are easily overcome by the reduction of preassure.

8.1.1 Solution

The forces holding the gas molecules to the solid are are easly overcome by either the application of heat or the reduction of preassure; either of these methods can be used to regenerate the adsorbents.
See also the Le Chatelier's principle.

8.2. Sizing a DSI Injection System. Calculate the minimum pipe (or duct) volume

Design a DSI – dry sorbent injection system - of an alkaline base in a flue gas duct.
Are given the following data:

- gas flow at the injection point, G: 108,000 m^3/h,
- circular duct;
- duct residence time,
- t_r: 1.0 seconds;
- flue-gas velocity, v: 20 m/s.

In your opinion which could be the problems related to high velocity of the flue gas in the duct?

Calculate the duct diameter (D) and the required duct length (L), that is the distance required between the injection point and the downstream particulate control device.

Theoretical Sorbent Residence Time in the **Duct**, **t_r = V/G**
V = reactor volume, $V = t_r\, G$
G = reactor flow rate.

8.2.1 Solution

Problems with high velocity:

- increase of drop preassure: $\Delta P \rightarrow v^2$
- problem of noise;
- erosion due to the dusts.

$G = 108{,}000\ m^3/h\ /\ 3{,}600\ s/h = 30\ m^3/s$
$t_{residence} = V / G$; **V** = t x G = 1 x 30 = **$30\ m^3$**
$G = A \times v$; $A = G/v = 30 / 20 = 1.5\ m^2$
$A = \pi D^2/4$; D = 1.38 m
$V = A \times L$; L = V/A = 30/1.5 = 20 m

Because of short residence time - both for mixing and reaction - only fast reactions/processes can occur inside the reactor. The use of fine solid particles and high temperature is a good starting point.
A sufficient length of ductworks is necessary to ensure a sufficient residence time.

8.3. Limits of dry sorbent injection

Dry sorbent injection (DSI) of $NaHCO_3$/$Ca(OH)_2$ for the neutralization of acid gases (e.g. HCl) is a very attractive technique. Can it be used with all HCl containing wastegases?

8.3.1 Solution

NO, because **chemical reaction is effective only with hot gases (T > 140°C)**

8.4. Cost of reactants

$CaCO_3$ is much cheaper than $NaHCO_3$/$Ca(OH)_2$. Then, would you recommend using it in DSI, instead of the two aforementioned reactants?

8.4.1 Solution

NO, because $CaCO_3$ is weak as a base, no reaction occurs under mild/medium temperatures, typical of DSI (140 – 200/250°C) in dry conditions

8.5. Flow increasing

In dry sorbent injection, can the injection of sodium bicarbonate increase the volumetric flow of flue gas? Why?

8.5.1 Solution

Yes, the volumetric flow of the flue gas can increase because a product of the reaction is CO_2.
$HCl(g) + NaHCO_3(s) \rightarrow NaCl(s) + H_2O(g) + \mathbf{CO_2(g)}$

8.6. Solvay's process

Report the overall Solvay's process to regenerate sodium carbonate

8.6.1 Solution

$2\ NaCl + CaCO_3 \rightarrow Na_2CO_3 + CaCl_2$

8.7. Dew point in SDA and DSI

Why is the dew point of cleaned flue gas from a SDA higher than from a DSI (dry injection)?

8.7.1 Solution

Because the absolute humidity (H) increases. See the lecture on Dew Point

9. GAS ABSORPTION TECHNIQUES

9.1. Designing packed bed tower

A 10,000 acfm (283,2 m^3/min) exhaust from a heat treating process contains 25 mole percent ammonia, and the average exhaust conditions are 30°C and 1.0 atm.
The efficiency of ammonia removal is 95% based on the following design parameters:

- Average tower temperature is 30°C
- Tower preassure is 1.0 atm
- Pure water is used as absorbing liquid
- Water rate is 1.5 times minimum
- Packing is 1.0-in. Ceramic Rasching rings

Estimate:

a) Lmin
b) The diameter of the packed tower

9.1.1 Solution

a) Liquid rate estimation

For the equilibrium curve for ammonia use the values reported in Annex 4.b “00_ANNEX 4b_Solubility data”

Use the following expressions to define the equilibrium curve:

$$ye = \frac{P_A}{760}$$

$$xe = \frac{\frac{C_A}{17}}{\frac{C_A}{17} + \frac{100}{18}}$$

Where:

- Xe is the concentration of the chemical in liquid at equilibrium with the gas phase (mole NH_3/mole liquid)
- Ye is the concentration of the chemical in gas at equilibrium with the liquid phase (mole NH_3/mole gas)

The adjusted data for the equilibrium curve of ammonia are reported in Table 1.

Table 1. Data for the determination of the ammonia equilibrium curve

CA	xe	Pa	ye
g NH_3/100 g H_2O	mole NH_3/mole liquid	mm Hg	mole NH_3/mole gas
0	0,00	0	0,00
2	0,02	19,3	0,03
3	0,03	29,6	0,04
4	0,04	40,1	0,05
5	0,05	51	0,07
7,5	0,07	79,7	0,10
10	0,10	110	0,14
15	0,14	179	0,24
20	0,17	260	0,34
25	0,21	352	0,46

Now consider the following configuration:

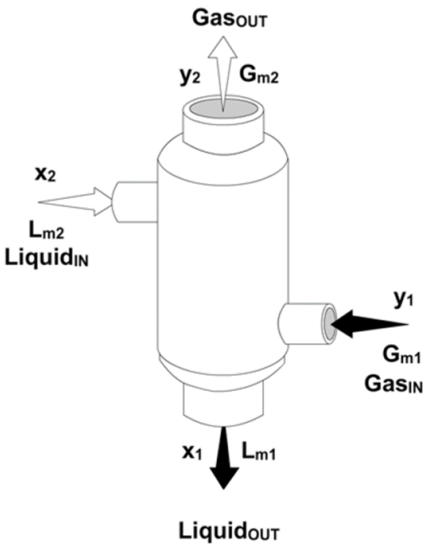
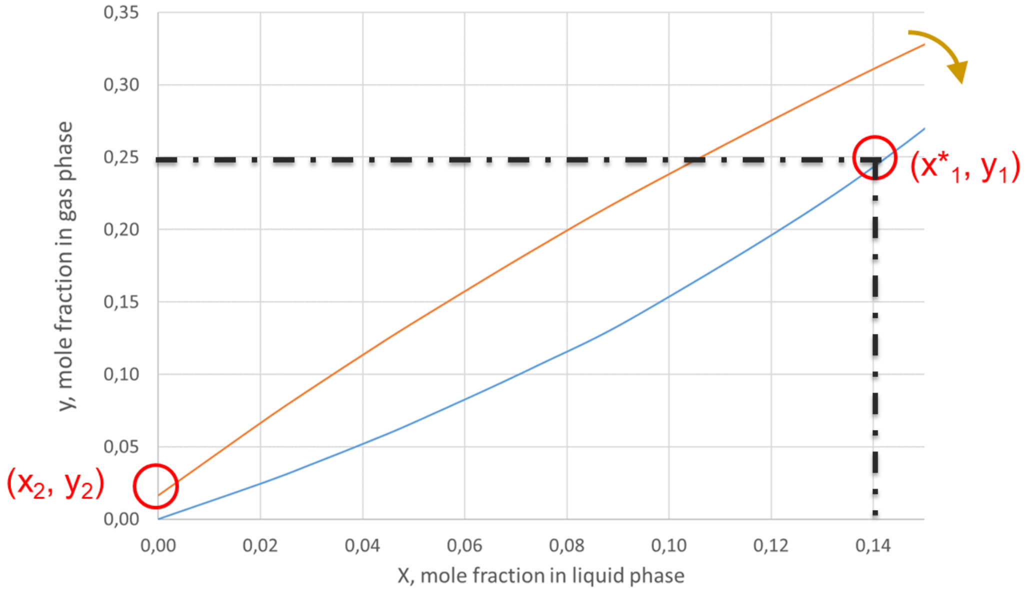


Figure 1. Schematization of a counter current packed bed tower

We base the calculation on 1 mole of entering gas.
Moles of air entering (G'm)=0.75 moles
Moles of NH_3 entering= 0.25 moles
Y1= 0.25 moles/1 mole =0.25
Moles of NH_3 leaving= 0.25*(1-0.95/100) ≈ 0.0125 moles
Moles of air leaving leaving= 0.75 moles (this flux doesn't changes)
Total mass of flue gas leaving the unit =0.0125+0.75 = 0.7625 moles
Y2 = 0.0125/0.7625 ≈ 0.0164
Since fresh (not recirculated) water is used, x_2 is zero.

The operating lines are not straight, the minimum slope operating lines is defined as the straight line connecting points (x2, y2 and x*1, y1 and has slope (L'mmin/G'm)

$$G'_m * \left(\frac{y_1}{1-y_1} - \frac{y_2}{1-y_2}\right) = L'_{m,min} * \left(\frac{x*_1}{1-x*_1} - \frac{x_2}{1-x_2}\right)$$



$$0.75 * \left(\frac{0.25}{1-0.25} - \frac{0.0164}{1-0.0164}\right) = L'_{m,min} * \left(\frac{0.14}{1-0.14} - \frac{0}{1-0}\right)$$

$L'_{m,min}$=1.457 mol H2O/mol gas

The actual water rate is:

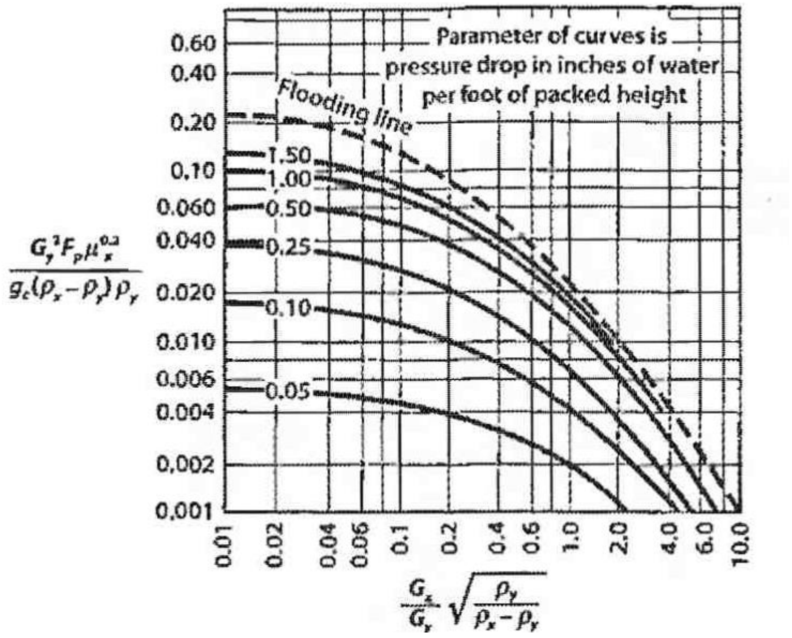
$L'_{m,a}=1.5*1.457=2.186 \text{ mol H2O/mol gas}$

b) Tower section

Molecular weight of enetering gas= 0.75*29+0.25*17= 26 g/mol
Conversion factors
1 lbm(pound mass) = 453.59237 g
1 ft = 0,3048 m
Density of water =ρx= 62.15 lb/ft^3
Density of air =ρy= (P*MW)/ (R*T)= 0.0652 lb/ft^3

$$\frac{G_x}{G_y} * \sqrt{\frac{\rho_y}{\rho_x - \rho_y}} = \frac{L}{G} * \sqrt{\frac{\rho_y}{\rho_x - \rho_y}} = \frac{2.186 * 18}{1.0 * 26} * \sqrt{\frac{0.0652}{62.15 - \ 0.0652}} = 0.047$$

We insert this value in the following chart:



Where we obtain:

$$\frac{{G_y}^2 * F_p * {\mu_x}^{0,2}}{gc * (\rho_x - \rho_y)\rho_y} = 0.195$$

$$G_y = \sqrt{0.195 * \frac{gc * (\rho_x - \rho_y)\rho_y}{F_p * {\mu_x}^{0,2}}}$$

With:

- gc=units conversion factors =32.17 ft*lbm/s^2*lbf
- μ_x = liquid viscosity cp (0.8)
- ρ_x = liquid density lbm/ft^3
- ρ_y = gas density lbm/ft^3
- $Fp =$ 155 (see table for specific packing elements in the slides)

Now we can obtain the theoretical gas mass flux that determines the flooding in the tower:

G_y=0.413 $lb_m/(s*ft^2) \approx 2016\ g/s *m^2$

Therefore,
Actual flow G_y *= $G_y/2 \approx 1008\ g/s *m^2$

G = 283.2 m^3/min = 4.72 m^3/s

Use the ideal gas law to convert the units g/s !!!!
G = 4935.7 g/s
Therefore, the section of the tower can be estimated as:

S= G/G'= 4935/1008= 4,89 m2

The diameter is:

$$diameter = \sqrt{\frac{S*4}{\pi}} \approx 2.5\ m$$

9.2. Packing system requirements

In your opinion which are the most important requirements that a packing system should have?

9.2.1 Solution

- High wetted area per unit volume
- Minimal weight
- Sufficient chemical resistance
- Low liquid holdup
- Low preassure drop
- Low cost

9.3. Blow-down liquor in wet scrubber

The SO_2 concentration in a flue gas is: 500 mg/Nm^3; 90% of the SO_2 is removed by a Wet Scrubber.
Because of specific blow-down liquor aeration, all absorbed SO_2 is converted to SO_4^{2-}. The Italian limit value for waste water discharged in surface waters is 1000 mg/litre. How many m^3/day of water must be discharged to surface water to comply with the limit if the raw gas flow is 100,000 m^3/h? (Atomic weights: S =32; O =16)

9.3.1 Solution

Mass flow of SO_2 in the raw gas: 100,000 m^3/h x 500 mg/Nm^3 = 50 kg/h (we refer to N.C.., because no other temperature or pressure are indicated).
n = 90%; scrubbed SO_2=50 kg/h x 90% = 45 kg/h; mass of SO_4^{2-} to be discharged: 45 x SO_4/SO_2 = 45 x 96/64 = 67.5 kg/h.

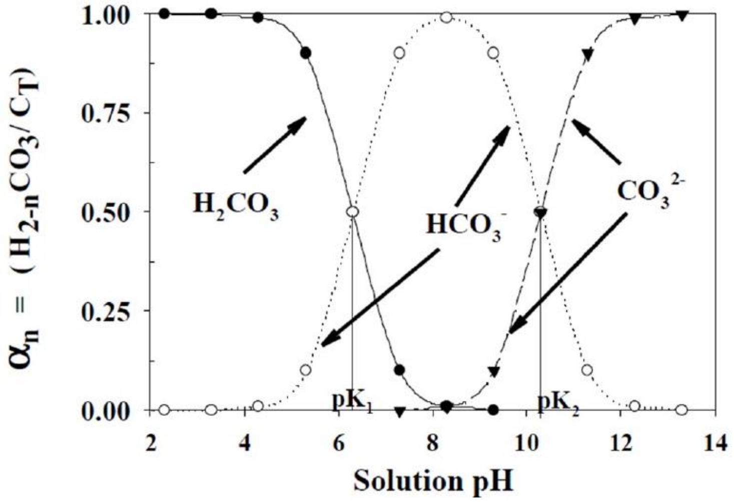
1 m^3 : 1.0 kg = x m^3 : 67,5 kg; therefore x = 67.5 m^3/h (= 1620 m^3/day)

9.4. Exercise: CO2 absorption

The global concentration of CO_2 in the atmosphere *has* reached *400 parts per million* (ppm) (v/v).

a. How much CO_2 (MW = 44) can be absorbed by an alkaline (pH > 12) wet scrubber from an air flow of 10,000 Nm^3/h? Express the flow mass of CO_2 in kg/h.

b. Write the chemical process at the set pH 12 *(CO_2 acidity constants: $pK_{a1} = 6.35$; $pK_{a2} = 10.3$)*



c. How much sodium hydroxide (MW = 40) is consumed? Express the flow mass in kg/h.

9.4.1 Solution

a) CO_2 content = 0.4 l/m^3 of air; total amount of CO_2 = 0.4 x 10000 = 4000 l at n.c. (=4000/22.4 = 178.5 mol CO_2/h
Mass of CO_2 that can be absorbed= n_{CO2} x MW_{CO2} = 178.5 x 44 =7.8 kg/h.

b) Write the balanced chemical equation:
2 NaOH + CO_2 = Na_2CO_3 + H_2O (or CO_2 + 2 OH^- = CO_3^{2-} + H_2O)

At pH > 12, all HCO_3^- is converted in CO_3^{2-}. (You can understand it better from the Graphic of species distribution vs. pH, or from the formula:
pH = pKa2+ log [(base)/(acid)]; → Log ([CO_3^{2-}]/[HCO_3^-]) = 12 – 10.3 = 1.7; [CO_3^{2-}]/[HCO_3^-] = $10^{1.7}$ = 50
Conclusion: at pH 12, 98% is carbonate ion and only 2% is bicarbonate ion, i.e. ≅ 100% CO_3^{2-}

c) mass of NaOH to neutralize all CO_2 = n_{NaOH} x 40;
From reaction(s) below we obtain: n_{NaOH} =2 x n_{CO2}; hence: m_{NaOH} consumed = (178.5 x 2) x 40 = 14.3 kg/h.

9.5. Wet scrubber: HCl removal

An air flow with 0.1% by volume of HCl is wet scrubbed counter-currently with water; the minimum removal efficiency required is 97.0%. The air flow is 10000 m^3/h; $T_{air\ flow}$ = T_{water} = 20 °C, P=1 atm; Henry's law constant for HCl: 1500 M/atm; MW(HCl): 36.5. Calculate:
A. Inlet and exit concentration in ppm;
B. Maximum concentration of $HCl_{(aq)}$ (mol/l) in the scrubbing liquor to comply with the above air emission concentration.
C. Minimum aqueous solution bleed rate (m^3/h)
D. Does the calculated concentration - b) above) - comply with the National limit for wastewaters to be discharged in surface waters: [Cl^-] = 1200 mg/L? If it does not, what technical operations would you suggest?

9.5.1 Solution

A. Inlet [$HCl_{(g)}$] conc.: 1000 ppm ; Exit [$HCl_{(g)}$] conc.: 30 ppm
B. Maximum concentration of $HCl_{(aq)}$ in the scrubbing liquor to comply with the above air emission concentration=30 *10-6 *1500= 0.045 mol/L;
C. Minimum aqueous solution bleed rate: **9.0** m^3/h

(1000 ppm-30ppm) *10000 m^3/h ≈ 0.40 kmol/h of HCl to be absorbed
c=n/V hence: V=n/c = 400 mol/h / 0.045 mol/L = 9.0 m^3/h)
E. NO
0.045 mol/L x MW = 0.045 x 35.5 = 1.60 g/L

Operations that can be suggested:
1. Use of two wet-scrubbers in series: 1st WS to recover HCl and obtain concentrated aq. HCl, to be used in the plant, if possible; 2nd WS with water, or aq. NaOH, to achieve the required removal efficiency (97%);
2. Use other plant's wastewaters to get [Cl^-] < 1200 mg/L (about 3 m^3/h are required; no more water from public water works or private wells!).

9.6. Wet scrubber: SO_2 removal

The SO_2 concentration in a flue gas is 100 mg/Nm^3, 20 mg/Nm^3 is the design target value of the cleaned gas. At the operating temperature (25 °C, p = 1.0 atm), Henry constant in water is $K_{H(SO2)}$ = 1.23 M/atm. What is the minimum fresh liquid-to-gas ratio (*L/G in liter/m^3*), to get 20 mg/Nm^3 at the exit of the wet scrubber? MW (SO_2) = 64,

9.6.1 Solution

Exit $P_{SO2} = V_{SO2}/V \times Ptot = [(20/64)*22.4\ cm^3 / 1000000\ cm^3] \times 1 = 7.0 \times 10^{-6}$ atm;
max $c_{SO2} = K_H \times P_{SO2} = 1.23$ M/atm x 7.0×10^{-6} atm = 8.6×10^{-6} M;
n_{SO2} to be removed = 80 mg / 64 = 1.25 mmol/m^3 flue gas.
The volume required is: $c_{SO2} = n_{SO2}/V$; $V = n_{SO2} / c_{SO2} = 1.25 \times 10^{-3} / 8.6 \times 10^{-6}$ M = 145 L fresh water / m^3 flue gas

Note: too high! Currently, L/G < 3.0 L/m^3, ≅ 95% of which is recycled liquor!! ..you cannot remove sufficient SO_2 with plain water, addition of a chemical base (CaCO3, Ca(OH)2, NaOH) is always required!)

9.7. Wet scrubber - drawbacks

One possible drawback to the use of wet scrubbers is that the flue gas temperature is cooled to its adiabatic saturation temperature. Report your considerations concerning the resons to apply a flue gas reheating after the scrubber.

9.7.1 Solution

- to avoid H_2O vapour condensation;
- to avoid/reduce plume visibility *(and: raise the emitted plume; avoid/reduce chemical corrosion).*

9.8. Scale buildup in wet scrubber

deposit or scale buildup (mainly $CaCO_3$, but also $CaSO_3/CaSO_4$ with flue gases) in wet scrubbers can be avoided by the application of the following measures:

- using the strong base_____for acids ionisation/neutralization;
- keeping the pH as _____ as possible;
- _________the blow-down rate
- keeping a _____ level of dissolved salts in the scrubbing liquid;
- _____ the scrubber inlet gas temperature;
- _____ the scrubber outlet gas temperature;
- _____ the scrubber liquid temperature.

Complete the sentences with the missing word. Explanations are not necessary.

9.8.1 Solution

- using the strong base NaOH for acids ionisation/neutralization,..Ca-salts have lower solubilities than Na-salts
- keeping the pH as low as possible,…to prevent the formation of CO_3^{2-}
- increase the blow-down rate, ..to reduce TDS concentration and to prevent saturation
- keeping a low level of dissolved salts in the scrubbing liquid, ..to reduce TDS concentration and to prevent saturation
- decrease the scrubber inlet gas temperature, ..to reduce water evaporation, hence ..to reduce TDS concentration and to prevent saturation

- decrease the scrubber outlet gas temperature, ..to reduce water evaporation, hence ..to reduce TDS concentration and to prevent saturation
- decrease the scrubber liquid temperature. ..to reduce water evaporation, hence ..to reduce TDS concentration and to prevent saturation

9.9. Removal of SO_2 and HCl in wet scrubbers

Wet scrubbers are often the technology of choice for high removal rate of acid gases. Which is correct A) or B)? ….
A. SO_2 is more difficult to remove than HCl, but removal rates greater than 95% can be achieved.
B. HCl is more difficult to remove than SO_2, but removal rates greater than 95% can be achieved.
Explain your choice.

9.9.1 Solution

The correct answer is A. SO_2 is a weak acid, less reactive than HCl; high SO2 removal can be achieved with efficient WS by addition of selected chemical bases, i.e. strong $Ca(OH)_2$ and NaOH; also $CaCO_3$.

9.10. Wet scrubber efficiency

YES or NOT? A wet scrubber (WS) efficiency can be enhanced by:

- Increasing the liquid-gas interface area (Y/N)
- Providing good mixing of the gas and liquid phases (turbulence) (Y/N)
- Increasing the upward gas velocity (Y/N)
- Increasing the “residence” or “contact” time for the gas phase in the WS (Y/N)

9.10.1 Solution

- Increasing the liquid-gas interface area: YES
- Providing good mixing of the gas and liquid phases (turbulence): YES
- Increasing the upward gas velocity: NO
- Increasing the “residence” or “contact” time for the gas phase in the WS: YES

9.11. Packed tower –general questions

Q1. True or False? Packed towers have limited application for particulate removal.

Q2. Packed towers are frequently used for removing gaseous pollutants because:
a. The packing provides a large surface area for gas-liquid contact
b. The packing provides good mixing of gas and liquid and a long residence time
c. All of the above

Q3. Increasing the liquid flow rate in a packed tower will usually ____________________ the gas removal rate.
a. Increase
b. Decrease
c. Have no effect on

Q4. In a ____________________ packed tower, the gas stream being treated enters the bottom and flows upward through the packing while the liquid is introduced over the top of the packing and flows down through it.
a. Cocurrent
b. Crossflow
c. Countercurrent

Q5. A ____________________ packed tower cannot handle large variations in liquid or gas flow rates because flooding may occur.

a. Cocurrent
b. Countercurrent
c. Crossflow
d. Fiber-bed

Q6. Cocurrent packed towers usually have ____________________ pressure drops than countercurrent packed towers.
a. Higher
b. Lower

Q7. True or False? Crossflow packed towers can handle flue gas containing a high concentration of particulate matter because they use liquid sprays that will remove and wash away particles in the front half of the bed.

Q8. Packing material is usually made of:
a. Porcelain
b. Polyethylene
c. Polypropylene
d. All of the above

Q9. In a packed tower, liquid occasionally flows in little streams straight through the packing without wetting the packing surface. This condition is called:
a. Flooding
b. Liquid channeling
c. Mixing
d. Plugging

Q10. In packed tower, liquid is distributed over the packing by using:
a. Sprays
b. Sprays and small venturis
c. Sprays, weirs, and tubes
d. Chevron-shaped sheets and sprays

Q11. If the gas flow rate through a packed tower is too low, ____________________ may occur.
a. Flooding
b. Mixing
c. Gas channeling
d. Plugging

Q12. True or False? Packed towers are most suitable for industrial processes requiring high gas removal efficiency, but not having a high concentration of particulate matter in the flue gas.

Q13. True or False? Packed towers remove particulate matter and other solids more easily and with less maintenance problems than plate towers.

9.11.1 Solution

Q1. True
Packed towers have limited application for particulate removal.

Q2. d. All of the above
Packed towers are frequently used for removing gaseous pollutants for the following reasons:
- The packing provides a large surface area for gas-liquid contact
- The packing provides good mixing of gas and liquid and a long residence time

Q3. a. Increase
Increasing the liquid flow rate in a packed tower will usually increase the gas removal rate because of increasing the potential solubility of the pollutant in the additional liquid.

Q4. c. Countercurrent

In a countercurrent packed tower, the gas stream being treated enters the bottom and flows upward through the packing while the liquid is introduced over the top of the packing and flows down through it.

Q5. b. Countercurrent
A countercurrent packed tower cannot handle large variations in liquid or gas flow rates because flooding may occur.

Q6. b. Lower
Cocurrent packed towers usually have lower pressure drops than countercurrent packed towers. Because the liquid and gas streams move in the same direction in cocurrent packed towers, there is less resistance to flow.

Q7. True
Crossflow packed towers can handle flue gas containing a high concentration of particulate matter because they use liquid sprays that will remove and wash away particles in the front half of the bed.

Q8. d. All of the above
Packing material is usually made of porcelain, polyethylene, or polypropylene.

Q9. b. Liquid channeling
In a packed tower, liquid occasionally flows in little streams straight through the packing without wetting the packing surface. This condition is called liquid channeling.

Q10. c. Sprays, weirs, and tubes
In packed tower, liquid is distributed over the packing by using sprays, weirs, and tubes.

Distributor	Advantages	Disadvantages
Weirs	Handle dirty liquids with a high solids content Can use river or unfiltered water Can be easily inspected and maintened if access is available	Most costly to purchase Do not distribute liquid as uniformly as other methods Weirs must be level
Tubes	Uniform liquid distribution Can be buried below packing surface Generally least expensive to purchase	Easily plugged, must use filter Difficult to determine if holes are plugged when tube is buried in the packing
Spray nozzles	Uniform liquid distribution Tower need not be plumb Can be easily inspected and maintened if access is available	Highest pressure drops and operating costs Easly plugged, must use filter

(reference: Clark, J. M. 1975. Absorption equipment. In F. L. Cross and H. E. Hesketh (Eds.), Handbook for the Operation and Maintenance of Air Pollution Control Equipment. Westport: Technomic Publishing)

Q11. c. Gas channeling
If the gas flow rate through a packed tower is too low, gas channeling may occur.

Q12. True
Packed towers are most suitable for industrial processes requiring high gas-removal efficiency, but not having a high concentration of particulate matter in the flue gas. Packed towers are susceptible to plugging.

Q13. False
Packed towers do NOT remove particulate matter and other solids more easily and with less maintenance problems than plate towers. The tops of plates can usually be accessed through openings, while the middle of the packed bed cannot.

10. BIOFILTRATION

10.1. Biofiltration of H_2S

Convert the Henry's constant for H_2S at 1 atm and 30°C (see Appendix 4a) from the units given to units convenient for biofilter calculation:
$C_{g,i} = H_{D,i} * C_{L,i}$
Where:

- Cg,i= concentration of pollutant "i" in air (g/m3)
- CL,i= concentration of pollutant "i" in water (g/m3)
- Hi is the Henry's constant of compound-i, dimensionless, although the units really are (g/m3 in air) / (g/m3 in water)

Use this value to calculate the equilibrium concentration of H_2S that would exist in water if the concentration in air is maintained at 150 ppm at 1 atm and 30°C. The MW is 34.

10.1.1 Solution

From Annex 4a, the appropriate Henry's constant is $0.0609*10^4$ atm/mole fraction.
It is suggested that the conversion proceed in steps as follow.
$p_i = H_i * x_i$
Considering $p_i = y_i * p_t$ and dividing the previous expression per p_t
$H_i / p_t = y_i / x_i$
Multipying by molecular weight (MWi) of I the numerator and denominator to convert mole fractions (essentially moles I per mole air or water) to mass fraction:
$H_i / p_t = (y_i * MW_i) / (x_i * MW_i) = (mass_i / \text{mole air}) / (mass_i / \text{mole water})$
Convert mole of air to volume of air using the ideal gas law:
PV=nRT → mole air =PV/RT
Where P= 1 atm
R= 0.08206 L atm K−1 mol−1
Convert mole of water to volume of water:
1 kg = 1 l → 1000 g /18 g/mole = 1 l → 0.018 l

$$\frac{H_i}{p_t} = \frac{1000 * c_{g,i} * 0.08206 * T/p_t}{1000 * c_{L,i} * 0.0180}$$

$$H_i = \frac{c_{g,i}}{c_{L,i}} * 4.559 * T$$

Therefore,

$$H_{D,i} = H_i * \frac{0.2194}{T}$$

To solve the problem, first convert the air concentration of 150 ppm H2S to mass/volume units using:

$$C_{mass} = \frac{M_P}{V_t} = \frac{C_{ppm} * MW_P}{R * T/P} * 10^{-6}$$

C_{mass}= mass concentration, g/m^3
C_{ppm}= volume or molar concentration, ppm
P = preassure, Pa (1 atm=101325 Pa)
R= 8.314 Pa*m3/gmol*K

Cg,i = 0.205 g/m^3
$C_{g,i} = H_{D,i} * C_{L,i}$
CL,i = 0.465 g/m^3 = 0.465 mg/l

10.2. Biofiltration of H_2S

Considering the results of the previous exercise, is H_2S a good candidate for biofiltration? Why or Why not?

10.2.1 Solution

It is slightly soluble. Therefore, ethane is not a good candidate for biofiltration.

10.3. Biofiltration of ethane

Convert the Henry's constant for ethane at 20° (given in annex 4a) into units more suitable for use in analysing a biofilter. Is ethane a good candidate for biofiltration? Why or why not?

10.3.1 Solution

Cg,i =0.1871 g/m3
CL,i = 0.0095 g/m3
Comparing with H_2S, the solubility is very low. Therefore, ethane is not a good candidate for biofiltration.

10.4. Design a biofilter for a mixture of BTEX

A mixture of BTEX (benzene, toluene and xylene) vapors in air is to be controlled with a compost biofilters. A pilot plant with bed dimensions of 4 m * 1m * 0.75 m (deep) was operated with results as shown in the table. Other pilot-plant data include: gas flow = 5 m3/min, T=30°C, P= 1 atm, ΔP= 4 cm of water. The average molecular weight of the BTEX mixture is 92.

- Prepare a graph showing the elimination capacity as a function of the mass loading rate. What are the maximum efficiency and the maximum elimination capacity of the system? What is the critical load?
- Is the efficiency constant if the inlet concentration increase?

Table. Results from the experimental activity

Inlet BTEX conc.	Removal Efficiency
ppm	%
25	95
37.5	95
50	95
75	90
100	75
125	65
150	53
175	47
200	40

10.4.1 Solution

Covert the unit of ppm into g/m^3

$$C_{mass} = \frac{M_P}{V_t} = \frac{C_{ppm} * MW_P}{R * T/P} * 10^{-6}$$

C_{mass}= mass concentration, g/m^3
C_{ppm}= volume or molar concentration, ppm
M_p= mass of pollutant gas, µg
MW_p= molecular weight of pollutant gas, g/gmol
T= temperature, K
P = preassure, Pa (101325 Pa)
R= 8.314 Pa*m^3/gmol*K

Empty Bed Residence Time (EBRT)= (4m * 1m *0.75)/ 5m^3/min=0.6 min
Surface Loading (SL)=5 m^3/min / (4 m* 1 m) =1.25 m/min
Volume Loading (VL)= 1/EBRT= 1.667 min^{-1}
Mass Volume Loading (MLv)=VL* Ci

Elimination Capacity EC (g/m3 /hr) → $EC = ML_V \cdot \eta$

The experimental results can be used for the calculations reported in the following table:

Inlet BTEX conc.	Conc	Removal Efficiency	EBRT	MLV	EC
ppm	g/m3	%	min	g/m3*h	g/m3*h
25	0.09	95	0.6	9.25	8.79
37.5	0.14	95	0.6	13.88	13.18
50	0.19	95	0.6	18.50	17.58
75	0.28	90	0.6	27.75	24.98
100	0.37	75	0.6	37.00	27.75
125	0.46	65	0.6	46.26	30.07
150	0.56	53	0.6	55.51	29.42
175	0.65	47	0.6	64.76	30.44
200	0.74	40	0.6	74.01	29.60

The results are graphed in the following figure.

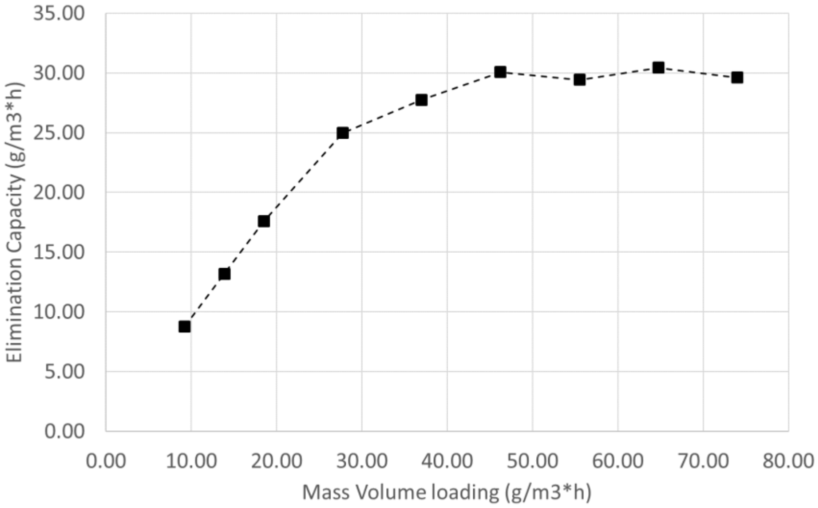


Figure. The graph is based on result from pilot plant test aimed at experimentally measure the Elimination capacity (quantity removed per unit time and per filter unit volume) VS Mass volume loading (quantity fed per unit time and per filter unit volume).

From the analysis of the table and of the graph, we can observe:

- The graph indicates what are the maximum efficiency (Slope of the initial linear trend) and the maximum elimination capacity ECmax of the specific system (plateau)
  - The maximum efficiency is 95%.
  - The maximum elimination capacity is 30 g/m3*h.
- At low loading rates EC varies linearly with MVL . The efficiency stays constant
- There is a point at which the EC begins to level out (Inflection point). The efficiency begins to drop off.
- The MVL at this point is called the Critical Load MLVC. The critical load appears to be about 20 g/m3*h

Our target is to establish the optimal ML_V to be applied and accordingly, the Volume required for the filter (V_f).
If we design for the maximum elimination capacity **ECmax**, the efficiency of the system could be very low. It is always suggestable to stay at the maximum efficiency, and thus below the **Critical Load ML_{VC}**
In the reference example, we can fix MLv=18,5 g/m^3/h <**ML_{VC}**
Since the Ci is known, VL can be derived from:

$$ML_V = VL \cdot C_i$$

Then, Vf=EBRT*Q= 0,6 min * 5 m^3/min= 3 m^3

10.5. Mathematical modelling

A pilot-plant biofilter to control styrene was built and operated to obtain data as follows: at superficial gas velocity of 0.5, 1.0 and 1.5 m/min, removal efficiencies of 63%, 39% and 28%, respectively, were observed. The bed depth was 0.5 m. Develop a set of graps that show how different efficiencies might be obtained by varying bed depht and gas velocity in the full-scale biofilter.

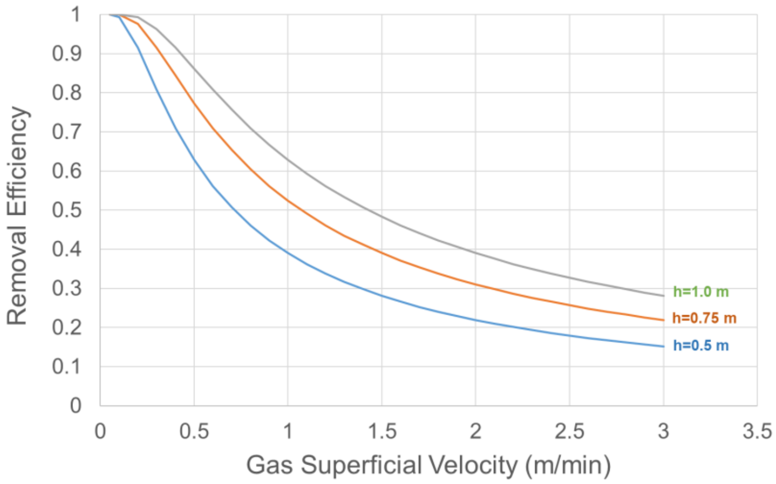
10.5.1 Solution

Plugging in the measured values for each of the three data points and averaging the three answers yields a value of R0=0.99 min-1 is obrained.

$$Ro = \frac{\ln(1-\eta)}{-h/u_g}$$

A graph for each of the conditions can be derived from the following expression:

$$\eta = 1 - exp\left\{-\frac{h * Ro}{u_g}\right\}$$



11. THERMAL AND CATALYTIC CONVERSION of NOX

11.1. SCR system

A power plant operates with 800 ppm NOX in the flue gas. The flue gas flow rate is 150000 m3/h at 300°C and 1 atm. An SCR system is being designed for 75% removal of NOx. Calculate the stechiometric amount of ammonia required in kg/day.
R= 8.20573E-05 m3 atm K−1 mol−1
MW NO= 30.01 g/mole
MW NO_2= 46,01 g/mol
MW NH_3 =17.031 g/mole

11.1.1 Solution

Volume= 1.50E+05 m^3/h
T=300 °C
Preassure= 1 atm
Assuming that NO_X is represented by the 100% of NO_2
n=(P*V)/(R*T)
Flow NO_2=2552.1 moli/h → 2552.1 *46/1000 = 117 kg/h
Efficiency = 0.75
8/6 moles of NH3 is required per 1 moles of NO_2.
Amount of ammonia =0.75*8/6*(2552.1*17.031)*24/1000=1043 kg/day

12. GAS STACKS AND PLUME RISE

12.1. Reducing local deposition of pollutants emitted from a stack

To reduce local deposition of pollutants emitted from a stack, you can (not exhaustive list):

- reduce the concentration of pollutants in the emitted waste gas
- reduce the mass flow of pollutant
- increase the temperature of the emitted waste gas
- increase the height of the stack
- increase the height of the plume
- reduce the exit stack area
- increase the exit stack area
- increase the residence time of the waste gas in the APCDs

Which of the above techniques do you think are suitable for this purpose?
What techniques do you suggest among those eligible?

12.1.1 Solution

To reduce local deposition of pollutants emitted from a stack, you can:

- reduce the concentration of pollutants in the emitted waste gas
- reduce the mass flow of pollutant
- increase the temperature of the emitted waste gas
- increase the height of the stack
- increase the height of the plume
- about the stack area we have to consider that the flow G = A x v, therefore if the stack area increase (or the diameter) the exit velocity decrease. A useful expression to use is the Holland's Equation.
- The resident time in the APCDs can reduce the deposition of pollutants emitted from a stack only if the removal efficiency in the single treatment units increases. Remember that if you need to increase the resident time of the flue gas in the APCD, you require a larger plant.

12.2. Plume rise

Plume rise (Δh) is the height that pollutants rise above a stack and is measured from the top of the stack to the upper edge of the plume.
a. True; b. False

12.2.1 Solution

b. False. Plume rise (Δh) is the height that pollutants rise above a stack and is measured from the top of the stack to the imaginary centerline of the plume rather than to the upper edge of the plume.

12.3. Plume rise

Plume rise from a stack is due to:
a. Heat and type of pollutant
b. Momentum and buoyancy
c. The composition of the stack gas
d. Height of stack
e. None of the above

12.3.1 Solution

b. Momentum and buoyancy. *Plume rise from a stack is due to momentum and buoyancy.*

12.4. Plume rise

Plume rise (effective plume rise) is due to (circle all correct)

a. Buoyancy
b. Height of stack
c. Momentum
d. only a and c

12.4.1 Solution

The correct answer is d.

12.5. Effective stack height

True or False? Effective stack height is determined by adding plume rise to the physical height of the stack.
a. True; b. False

12.5.1 Solution

a. True. *Effective stack height is determined by adding plume rise to the physical height of the stack*

12.6. Momentum term in plume rise

The momentum term in plume rise equations generally involves:
a. Ambient air temperature, wind speed, stack gas temperature
b. Wind speed, stack gas temperature, stack opening diameter
c. Stack gas velocity
d. Stack outside radius

12.6.1 Solution

c. Stack gas velocity. The momentum term in plume rise equations generally involves stack gas velocity.

12.7. Buoyancy in plume rise

True or False? Buoyancy terms in plume rise equations always depend on the difference between stack gas temperature and the ambient air temperature.
a. True; b. False

12.7.1 Solution

a. True. Buoyancy terms in plume rise equations always depend on the difference between stack gas temperature and the ambient air temperature.

12.8. Formulas for calculating plume rise

Plume rise formulas like those reported before are to be used on:
a. Plumes that are colder than the ambient air
b. Plumes that are hotter than the ambient air
c. Plumes that are the same temperature as the ambient air
d. None of the above

12.8.1 Solution

b. Plumes that are hotter than the ambient air. *Plume rise formulas like those reported here (developed by Briggs) are to be used on plumes that are hotter than the ambient air.*

12.9. Reheating gas before emission from stack

Stack gas, before entering the stack, is sometimes reheated in order to:

- Avoid condensation
- Enhance plume rise and pollutant dispersion
- Give better pollutant dispersion
- Avoid condensation and corrosion of ductworks and stack
- All of the above

12.9.1 Solution

All of the above

12.10. Unique stack for different flues

By putting more combustion flues inside the same stack we get: (circle the correct choices)
A) higher exit gas temperature from single flues;
B) higher plume rise;
C) lower plume visibility;
D) lower frequency of fumigation events nearby the stack;
E) the combustion flue gases inside the flue gas stacks are much hotter than the ambient outside air and therefore less dense than the ambient air

12.10.1 Solution

All of the above

12.11. Velocity reduction

Several air polluted streams from different processes are conveyed in the same stack; the exit air stream velocity is 18.6 m/s. If the total air flow is reduced by 60%, due to the shutdown of some activities, what will be the effective rate of emission?
What would you suggest to keep constant the exit velocity?

12.11.1 Solution

Solution a)
G1 = A x v1
Due to activities shutdown: G2 = A x v2
A1 = A2 = A (the stack exit section does not change!)
G2 = 0.4 x G1
v2 = G2/A = 0.4 x G1/A = 0.4 x [A x v1 /A] = 0.4 x v1 = 7.4 m/s

Solution b)
A decrease of the stack inner cross section!

12.12. Velocity reduction

Given that the stack gas velocity is 17 ms^{-1}, the internal stack diameter is 2.5 m, calculate the required stack diameter to increase the gas velocity to 22 ms^{-1}.

12.12.1 Solution

A narrower tip diameter is required.

$G = A_1 v_1 = A_2 v_2$

$A_2 = A_1 \times v_1 / v_2 = [3.14 \times (2.5)^2 / 4] \times 17/22 = 3.80\ m^2$

$D_2 = 2.2\ m$

12.13. Unique stack for different flues

Estimate the plume rise for a 2 m diameter stack whose the exit gas has a velocity of 34 m/s when the wind velocity is 4 m/s, the pressure is 1 atm, and the stack and surrounding temperatures are 85°C and 33 °C, respectively.

Use the Holland Equation:

$$\Delta h = \frac{V_s D}{u}\left(1.5 + 0.00268 \cdot P \cdot D \cdot \frac{(T_s - T_a)}{T_s}\right)$$

The meaning and the units of the parameters in the equation are supposed to be known by the students.

12.13.1 Solution

$\Delta h =$ plume rise, m

$V_s =$ stack exit velocity, m/s

$D =$ stack diameter, m

$u =$ wind speed, m/s

$P =$ pressure, mb (millibars)

$T_s =$ stack gas temperature, K

$T_a =$ ambient temperature, K

The solution is 38.9 m.

12.14. Effect of temperature on plume rise

The higher the temperature of a flue gas emitted from a chimney of the same plant, the higher / lower the plume rise, Δh: ....

The reasons are (choose the correct answers):

- hotter gases have higher/lower density: ....;
- hotter gases have higher/lower gas velocity: ....;

12.14.1 Solution

The higher the temperature of a flue gas emitted from a chimney of the same plant, the higher / lower the plume rise, Δh: higher

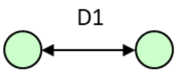
The reasons are (choose the correct answers):

- hotter gases have higher/lower density: lower.
- hotter gases have higher/lower gas velocity: higher.

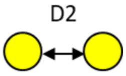
12.15. Stack configuration

Due to the increase of demand for MSW incineration, a 2nd identical WI line has to be built inside the existing incineration plant. To minimize the maximum ground concentration of pollutants, the best stacks configuration is looked for. **Choose the best one in each couple below:**

a) **config. A** (two separated, far away, single chimneys; each stack diam.=1.0 m), **or config. B** (two separated single chimneys, distance D_2 = 1.0 m; each stack diam.=1.0 m))? **......................**

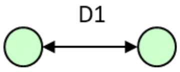


A)



B)

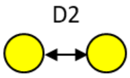
b) **config. A** (same above), **or config. C** (a new single chimney with a design exit gas speed equal to the one of the two single stacks (A)). Estimate the stack diam of config. D) in meter.



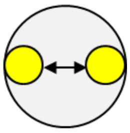
A)

C)

c) **config. B** (same as above), **or config. D** (same as config. A, but with the two flues in a single stack)? **...............**



B)



D)

12.15.1 Solution

Solution a) The configuration B is better

Solution b). The configuration C is better. Total cross-section area of two single flues: 2 x (3.14 x d^2/4) = 6.28/4 = 1.57 m^2. Cross-section area of the new single stack = 1.57 m^2; hence, D^2 = Section x 4/3,14 = 2; D = 1.4 m

Solution c) The configuration D is better.

13. WASTE PLANTS

13.1. Estimation of CH_4 and H_2 emissions from an Anaerobic Digestion Plant

Estimate the amount production of CH_4 and H_2S for a typical organic fraction of municipal solid waste with the composition given in Table below.
The values have to be expressed in m^3/kg MSW at T=35°C

Wet weight (kg)	Moisture content (%)	Elemental composition based on dry weight (%)					
		Carbon	Hydrogen	Nitrogen	Oxygen	Sulfur	Ash
9	70	48	6.4	2.6	37.6	0.4	5

Use the following chemical reaction for the anaerobic degradation:

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)H_2O \rightarrow$$
$$\left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + dNH_3 + eH_2S$$

The exercise aims to estimate the biogas production from experimental data of feedstock composition

13.1.1 Solution:

Step 1. Calculate the weight of H, O, N, C and S:

MC = 70%
Dry weight= 9 – 0.4(9)= 2.7 kg
Carbon=2.7*0.48=1.3 kg
Hydrogen=2.7*0.064=0.17 kg
Oxygen=2.7*0.376=1.02 kg
Nitrogen=2.7*0.026=0.07 kg
Sulfur=2.7*0.004=0.01 kg

Wet weight (kg)	Dry weight	Composition (kg)				
		Carbon	Hydrogen	Nitrogen	Oxygen	Sulfur
9	2.7	1.30	0.17	0.07	1.02	0.01

Step 2. Calculate the weight of H and O in moisture

Water content =Wet weight- Dry weight= 6.3 kg
Kg H= (6.3/18)*2=0.7
Kg O= (6.3/18)*16= 5.6

Element	Kg without water	Kg with water
C	1.30	1.30
H	0.17	0.87
O	1.02	6.62
N	0.07	0.07
S	0.01	0.01

Step 3. Divide each component by its respective molecular weight:

Element	Atomic weight	moles without water	moles with water
C	12.01	0.11	0.11
H	1.01	0.17	0.86
O	16	0.06	0.41
N	14.01	0.01	0.01

S	32.08	0.00	0.00034

Step 4. Determine the chemical formula

Determine the approximate formula with water (use sulphure as base and divide each value by the number of moles of sulphure.

Element	Mole ratio (with water) Sulfur=1
C	321
H	2567
O	1228
N	15
S	1

Chemical formula= $C_{321}H_{2567}O_{1228}N_{15}S$

Compare this value with the ones reported in the following table.

	Moisture content (w/w%)	Calorific value (kJ dry kg^{-1})	Approximate empirical formula
Cooked meat	45	25,335	$C_{181}N_{34}H_{331}O_{58}S$
Vegetables	94	14,627	$C_{156}N_{11}H_{287}O_{121}S$
Grass	46	18,122	$C_{29}NH_{56}O_{18}$
Kitchen paper	6	16,253	$C_{675}NH_{1268}O_{572}$
Fruit	81	15,327	$C_{667}N_8H_{1466}O_{591}S$
Cooked pasta	79	16,557	$C_{571}N_{20}H_{1138}O_{469}S$

Reference: Komilis, D., Evangelou, A., Giannakis, G., Lymperis, C., 2012. Revisiting the elemental composition and the calorific value of the organic fraction of municipal solid wastes. Waste Manag. 32, 372–381. doi:10.1016/j.wasman.2011.10.034

Step 5. Estimate the amount of CH_4 and H_2S from this equation:

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)H_2O \rightarrow$$
$$\left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + dNH_3 + eH_2S$$

Mole CH_4= 168 mole produced from 1mole MSW
Mole H_2S=1
In term of volume

PV=nRT
T=35 °C
R = 0.082 L atm K−1 mol−1
CH_4= 161 l/kg MSW
H_2S= 0.95 l/kg MSW

14. ASPIRATION SYSTEMS

14.1. Aspiration of a building

A concrete shed must be built to avoid diffuse odor emission generated by the primary treatment (screening and grit removal) of an urban WWTP. Air inside building will be conveyed through duct system and fan to an APC system consisting of wet scrubber + biofilter.
Figure 1 shows the plan and the section of the designed building and pattern of duct system. The height of the building will be 4m.

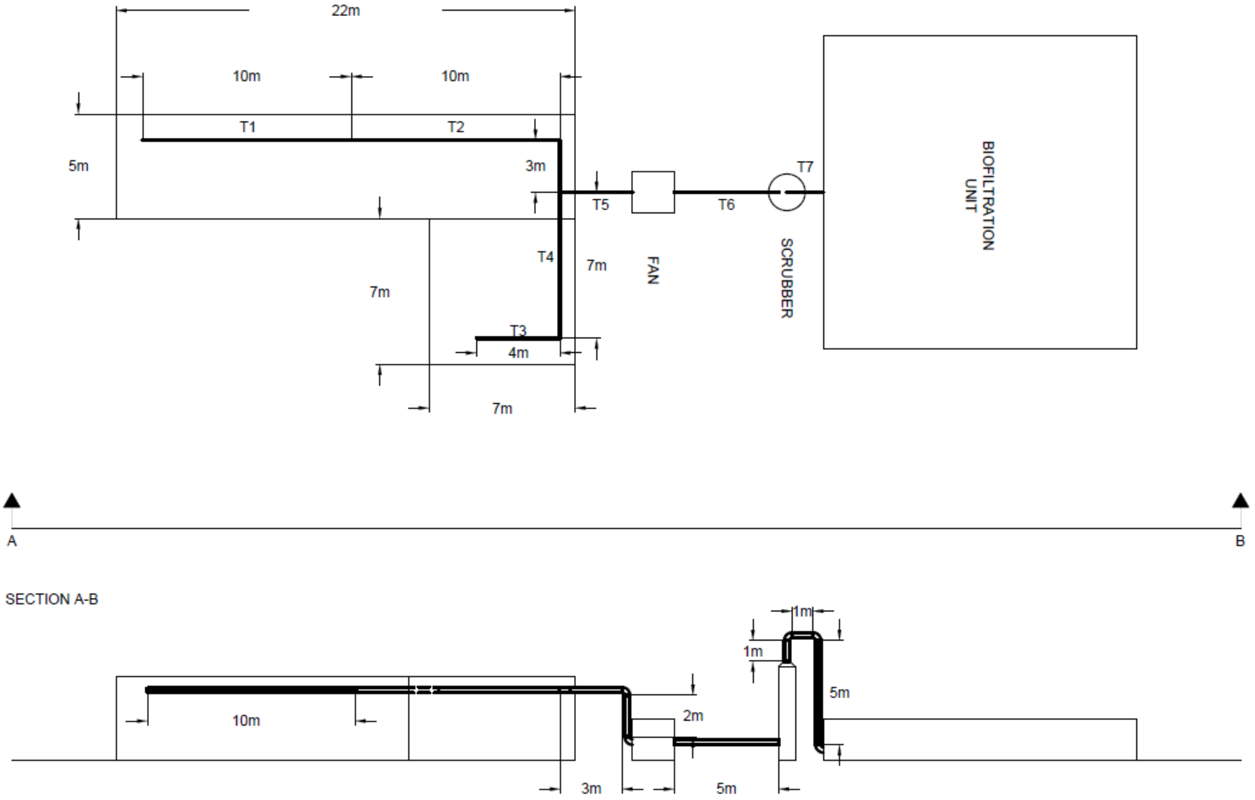


Figura 1 - Planimetry of Concrete shed and apc system

Question a) Design the duct system according to the list of commercially available ducts diameters shown in Table 1, following the good practice about velocity inside ducts. Consider a project temperature of 20°C. Round the project flowrate to the nearest thousand.

GALVANIZED STEEL DUCTS
Diameter (mm)
80
100
125
150
160
200
250
300
315
355
400
450
500

Project Flowrate Qn (0°C) Nm3/h
Project Flowrate Qp (20°C) m3/h

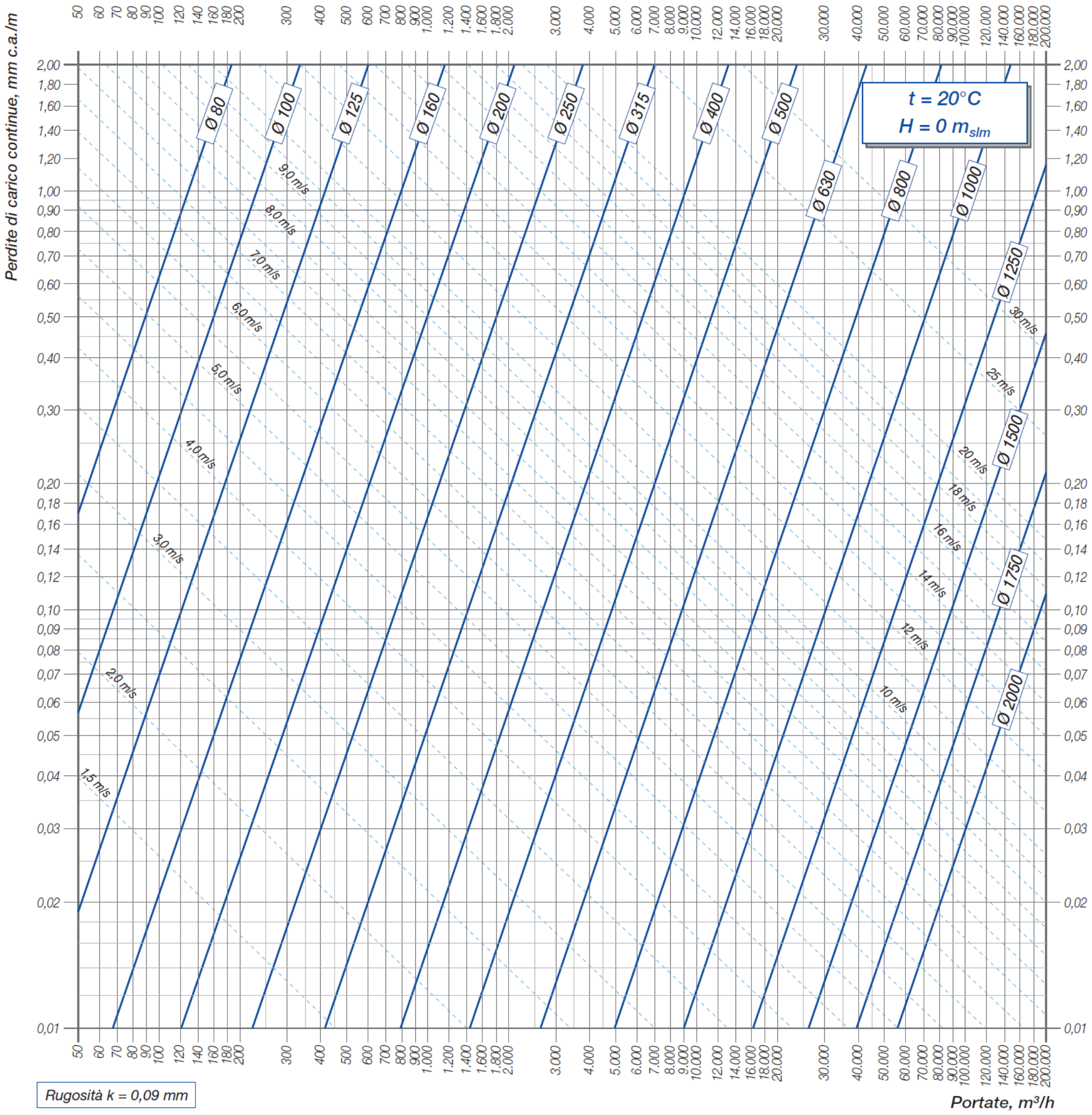
	L (m)	Qp (m3/h)	d (mm)	v (m/s)
T1	10			
T2	13			
T3	4			
T4	7			
T5	5			
T6	5			
T7	7			

Question b) Determine the design static pressure (Δp tot in mmH2O) to be provided by the fan. Consider an air density of ρ=1,2 kg/m^3 at 20°C and the specific coefficients as stated in the next Table.

rho_air (20°C)	1,2	(kg/m3)
ε **(90° bend)**	0,3	-
ε **(increasing of cross area)**	0,2	-
Scrubber Pressure Loss	100	mmH2O
Biofilter Pressure Loss	80	mmH2O

For the length specific pressure losses (r in mmH2O/m) for continuous head loss you can direct use the following figure, that is valid for :

- smooth circular ducts;
- temperature of 20°C;
- altitude of 0°C.



14.1.1 Solution

Question a1) Determination of the features of the airflow rate Q (Nm3/h)

H	m	4
Te air	°C	20
Buildings Vol	m3	636
Air changes/h	-	4
Qn (0°C)	Nm3/h	636*4=2544
Qe (20°C)	m3/h	2730
Qp	m3/h	3000

Referring to the Figure 1, the Qp must be conveyed to the APCDs from two separate areas. A flowrate of 2000 m^3/h must be aspirated from the first area by two segments: T1, conveying the first 1000 m3/h, and T2, conveying 2000 m^3/h. Equivalently, a flowrate of 1000 m^3/h must be aspirated by the second area by segments T3, conveying 500 m^3/h, and T4, conveying 1000 m3/h. The remaining segments T5, T6 and T7 must convey the total Qp of 3000 m3/h.

The velocity of the air flow should be in the range of 10 m/s < V < 20 m/s; therefore we can estimate the internal diameters for the GALVANIZED STEEL DUCTS.

	L (m)	Qp (m3/h)	d (mm)	v (m/s)
T1	10	1000	150	15.7

T2	13	2000	200	17.7
T3	4	500	125	11.3
T4	7	1000	150	15.7
T5	5	3000	250	17.0
T6	5	3000	250	17.0
T7	7	3000	250	17.0

Question b)

For the continuous and localized head losses use the expressions reported in the lecture.

CONTINUOUS HEAD LOSSES (identify the length specific head losses r (mmH2O/m) for each segment and multiply by the length (m) of the segment itself)

LOCALIZED HEAD LOSSES $r = \xi * \rho * \frac{v^2}{2*9,81}$ (mm H2O)

DUCTS- CONTINUOUS AND LOCALIZED (L) HEAD LOSSES

Ducts	**Type of Head Loss**	**Q (m3/h)**	**d (mm)**	**v (m/s)**	**L (m)**	**r (mmH2O/m)**	**ε**	**Δlc calc (mmH2O)**
T1								
	C	1000	150	15.7	10	1.8		18.00
T2								
	C	2000	200	17.7	13	1.8		23.40
	L (Expansion, A1/A2=0,6)	2000	200	17.7	-	-	0.2	3.83
	L (90° Bend, r/d=1,5)	2000	200	17.7	-	-	0.3	5.75
T3								
	C	500	125	11.3	4	1.6		6.40
T4								
	C	1000	150	15.7	7	1.8		12.60
	L (Expansion, A1/A2=0,6)	1000	150	15.7			0.2	3.03
	L (90° Bend, r/d=1,5)	1000	150	15.7			0.3	4.54
T5								
	C	3000	250	17.0	5	1.3		6.50
	L (T Confluence)	3000	250	17			1.3	22.96
	L (90° Bend, r/d=1,5)	3000	250	17			0.3	5.30
	L (90° Bend, r/d=1,5)	3000	250	17			0.3	5.30
T6								
	C	3000	250	17.0	5	1.3		6.50
T7								
	C	3000	250	17.0	7	1.3		9.10
	L (90° Bend, r/d=1,5)	3000	250	17			0.3	5.30
	L (90° Bend, r/d=1,5)	3000	250	17			0.3	5.30
	L (90° Bend, r/d=1,5)	3000	250	17			0.3	5.30
TOTAL								**149.11**

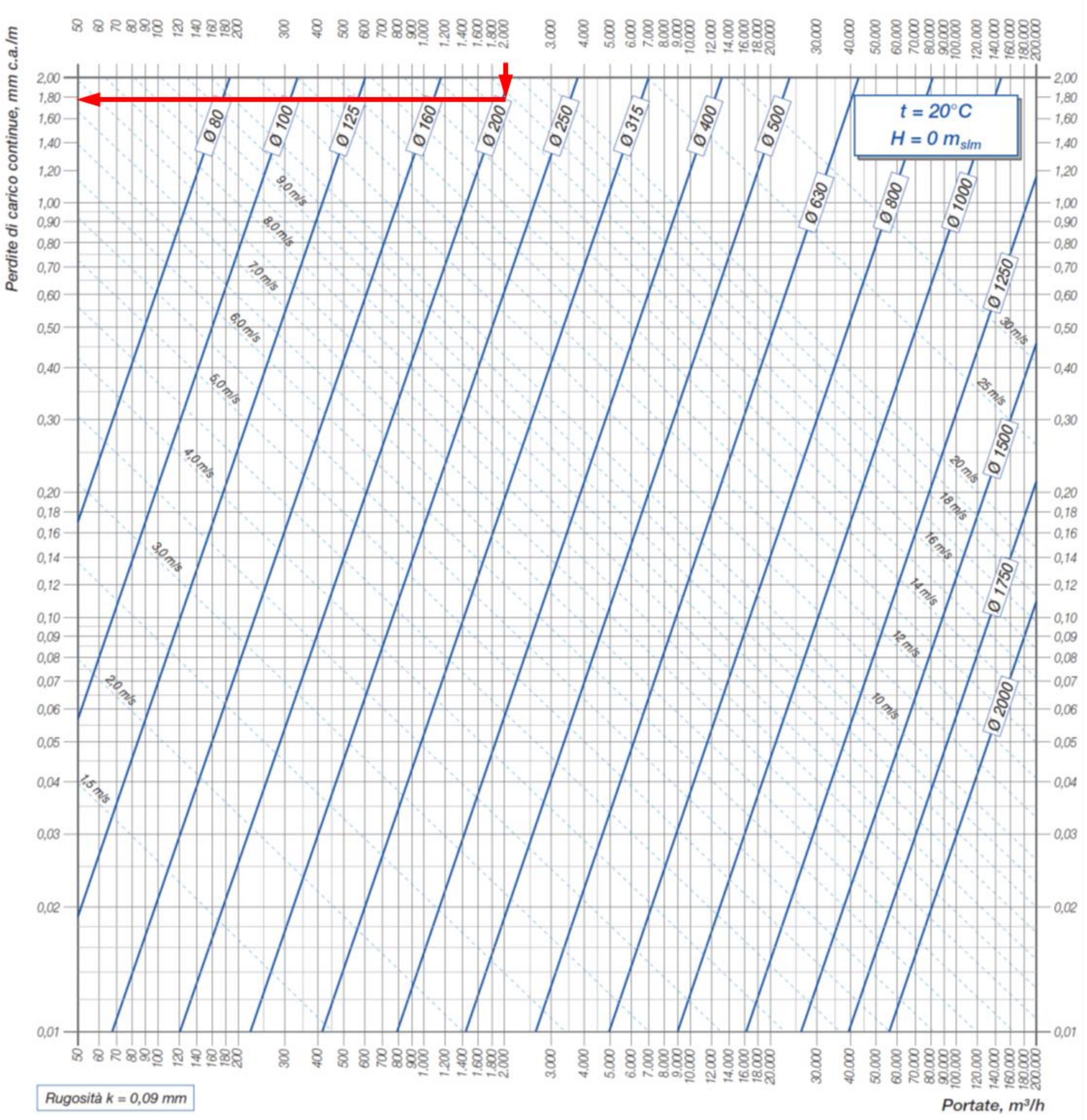
APCs- LOCALIZED (L) HEAD LOSSES

	Type of Head Loss	**Q (Nm3/h)**	**d (mm)**	**v (m/s)**	**L (m)**	**r (mmH2O/m)**	**ε**	**Δlc calc (mmH2O)**
Scrubber	L							100.00
Biofilter	L							80.00

TOTAL	**180.00**

The total head loss is 149.11+180 = **329.11 mmH₂O**

In the above table the length specific pressure losses (r in mmH2O/m) for continuous head loss is determined by the figure below where it is explained the case of a flow of 2000 m^3/h and a diameter duct of 200 mm.



14.2. Fan design

Choose the most suitable Fan (Model and materials for fan components) between the suggested Models (see following Technical brochures) able to work in the following conditions:

Project Flowrate at normal conditions	20.000,00 Nm3/h
Temperature of working	120°C
Static preassure	450 mm H_2O
Flowrate Features	Source of Polluted Gaseous Emissions: • Foundry, core-shooters • Foundry, pig-iron arc furnace

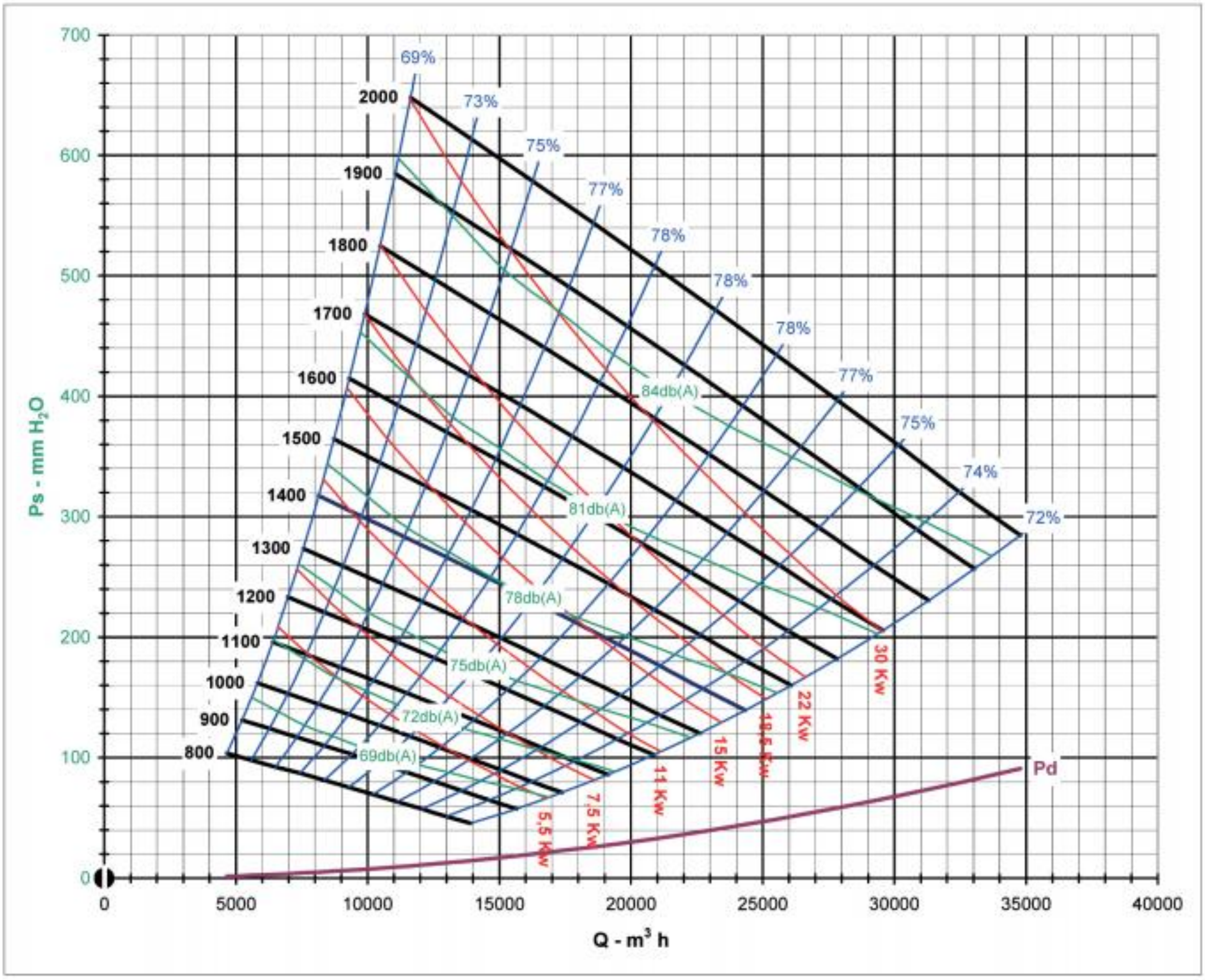
	Presence of - HCl - Ammines - Dust - Volatile Organic Compounds (BTEX, HCB)

Fan Model	
Installed Power	
Mechanical Efficiency	
Propeller Material	
Casing Material	

VENTILATORE Tipo	PTA	850/19		ø girante	839	standard
				altezza pala		standard
Fluido		Temp. di funz. °C	Altitudine m s.l.m.	Densità fluido		
ARIA	Densità standard 1,293	21,1	0	1,200		

Installazione di tipo B *

CURVA CARATTERISTICA ALLE CONDIZIONI DI FUNZIONAMENTO

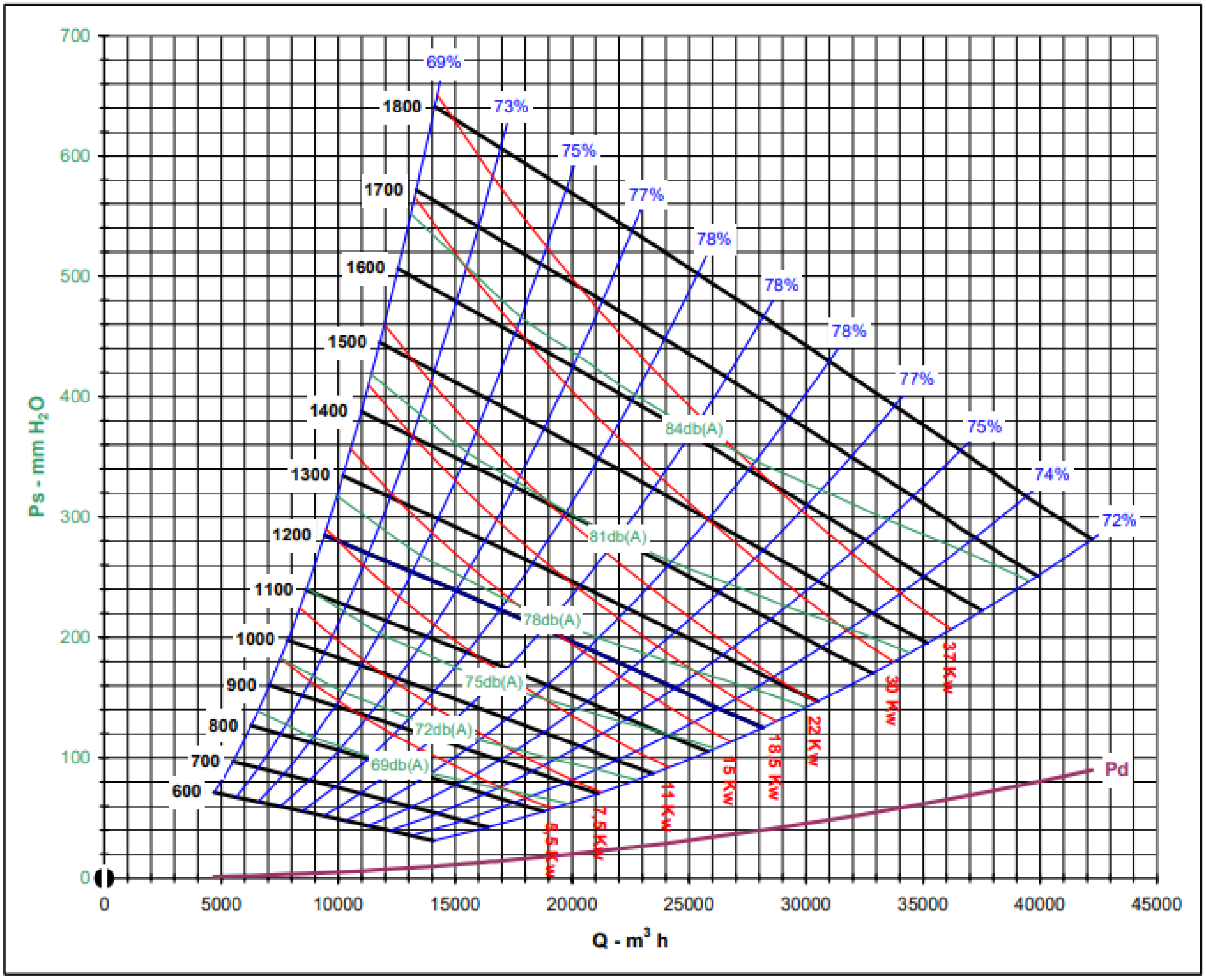


VENTILATORE Tipo	PTA	900/21		ø girante	927	standard
				altezza pala		standard

Fluido			Temp. di funz. °C	Altitudine m s.l.m.	Densità fluido
ARIA	Densità standard	1,293	21,1	0	1,200

Installazione di tipo B *

CURVA CARATTERISTICA ALLE CONDIZIONI DI FUNZIONAMENTO

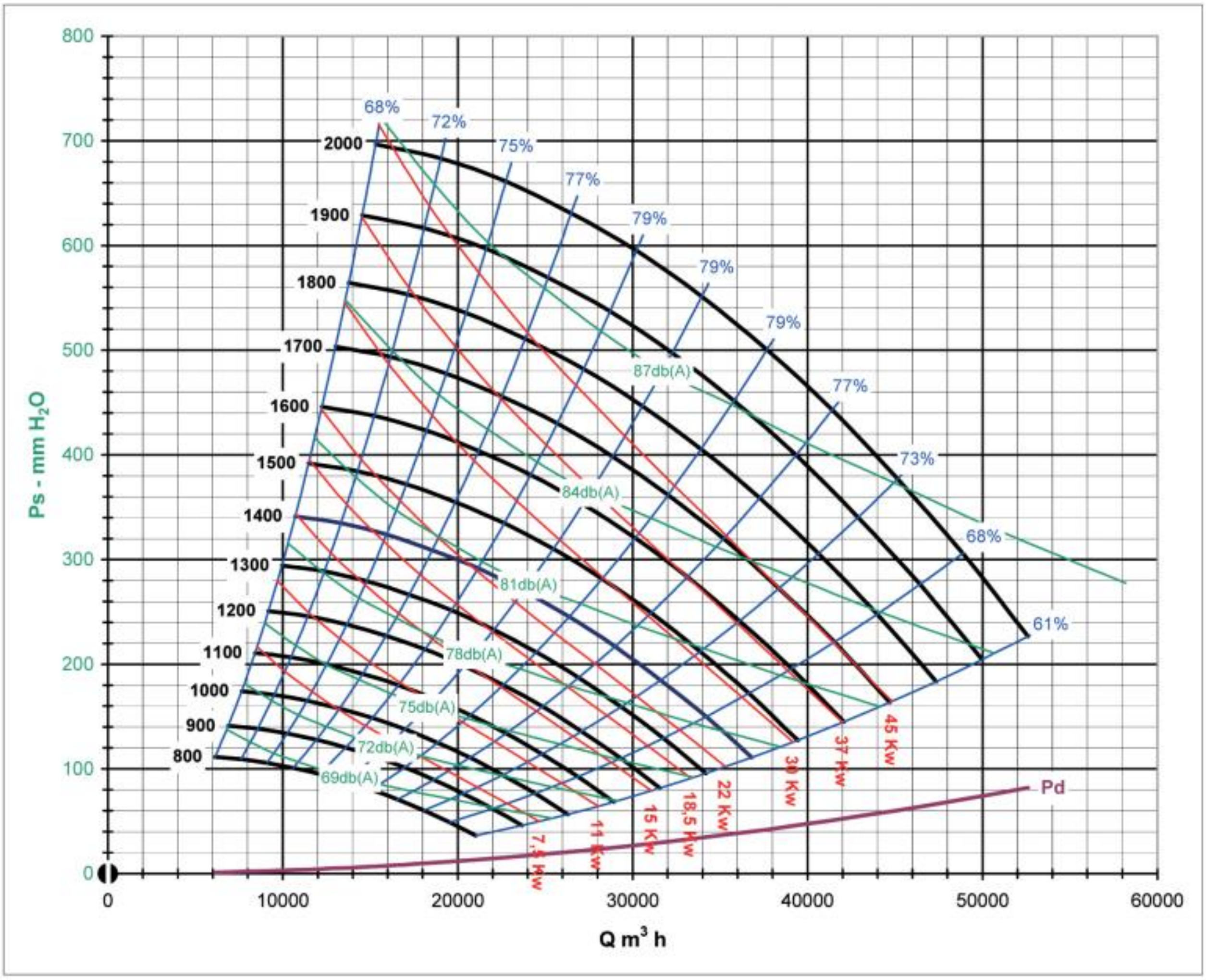


VENTILATORE Tipo	VTC	900		ø girante	900	standard
				altezza pala		standard

Fluido			Temp. di funz. °C	Altitudine m s.l.m.	Densità fluido
ARIA	Densità standard	1,293	21,1	0	1,200

Installazione di tipo B *

CURVA CARATTERISTICA ALLE CONDIZIONI DI FUNZIONAMENTO

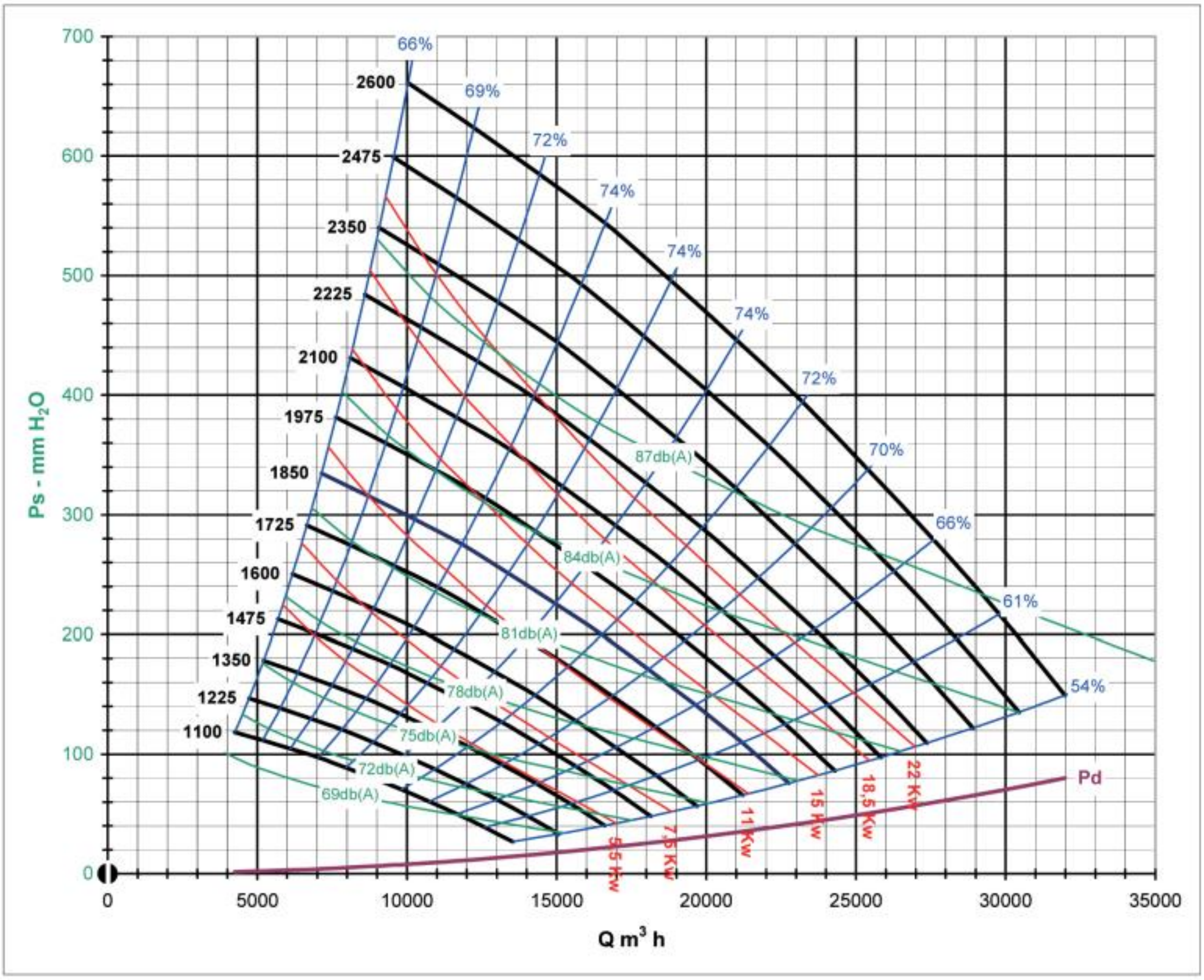


VENTILATORE Tipo	VTC	710		ø girante	710	standard
				altezza pala		standard

Fluido		Temp. di funz. °C	Altitudine m s.l.m.	Densità fluido
ARIA	Densità standard 1,293	21,1	0	1,200

Installazione di tipo B *

CURVA CARATTERISTICA ALLE CONDIZIONI DI FUNZIONAMENTO

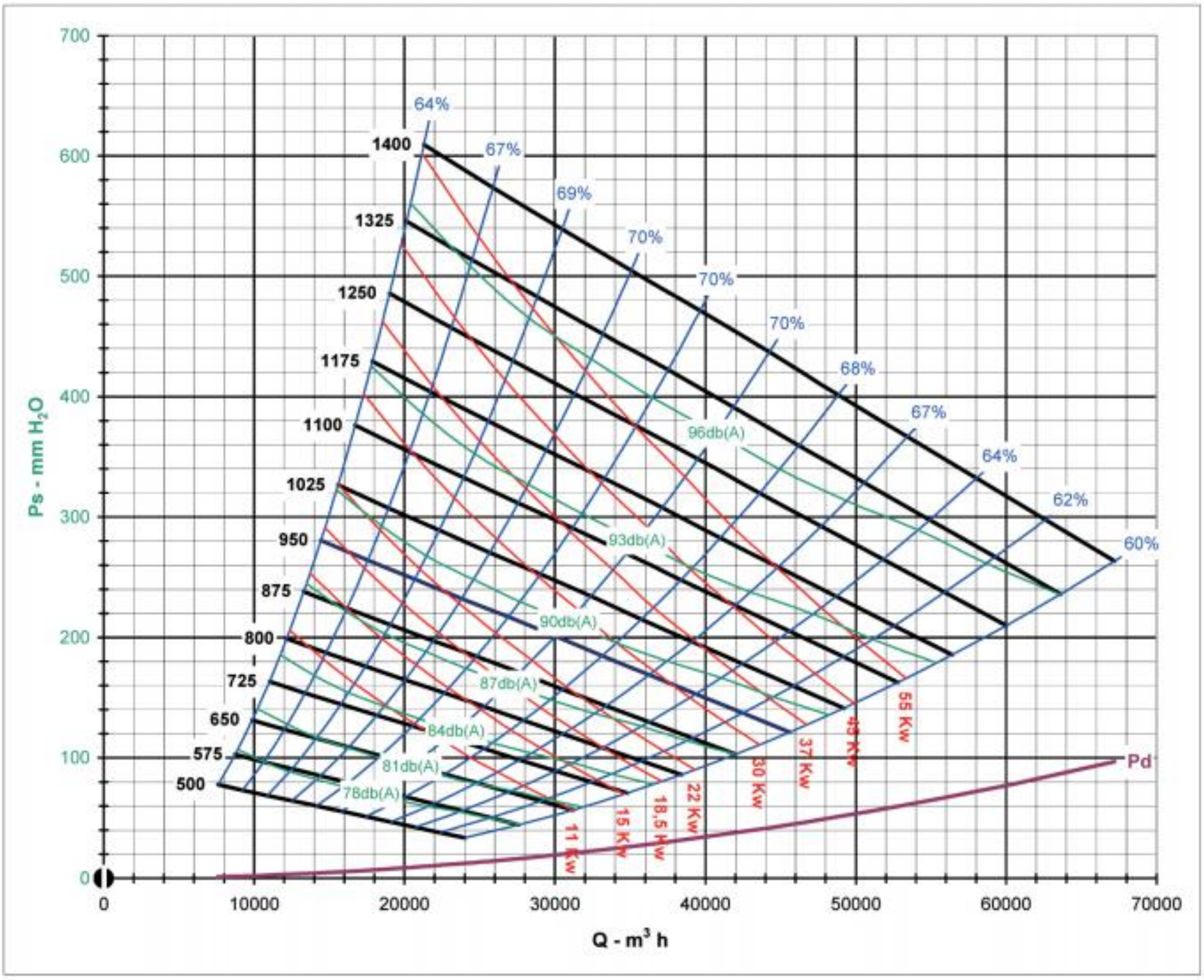


VENTILATORE Tipo	PTM	1150/26		ø girante	1150	standard
				altezza pala		standard

Fluido			Temp. di funz. °C	Altitudine m s.l.m.	Densità fluido
ARIA	Densità standard	1,293	21,1	0	1,200

Installazione di tipo B *

CURVA CARATTERISTICA ALLE CONDIZIONI DI FUNZIONAMENTO

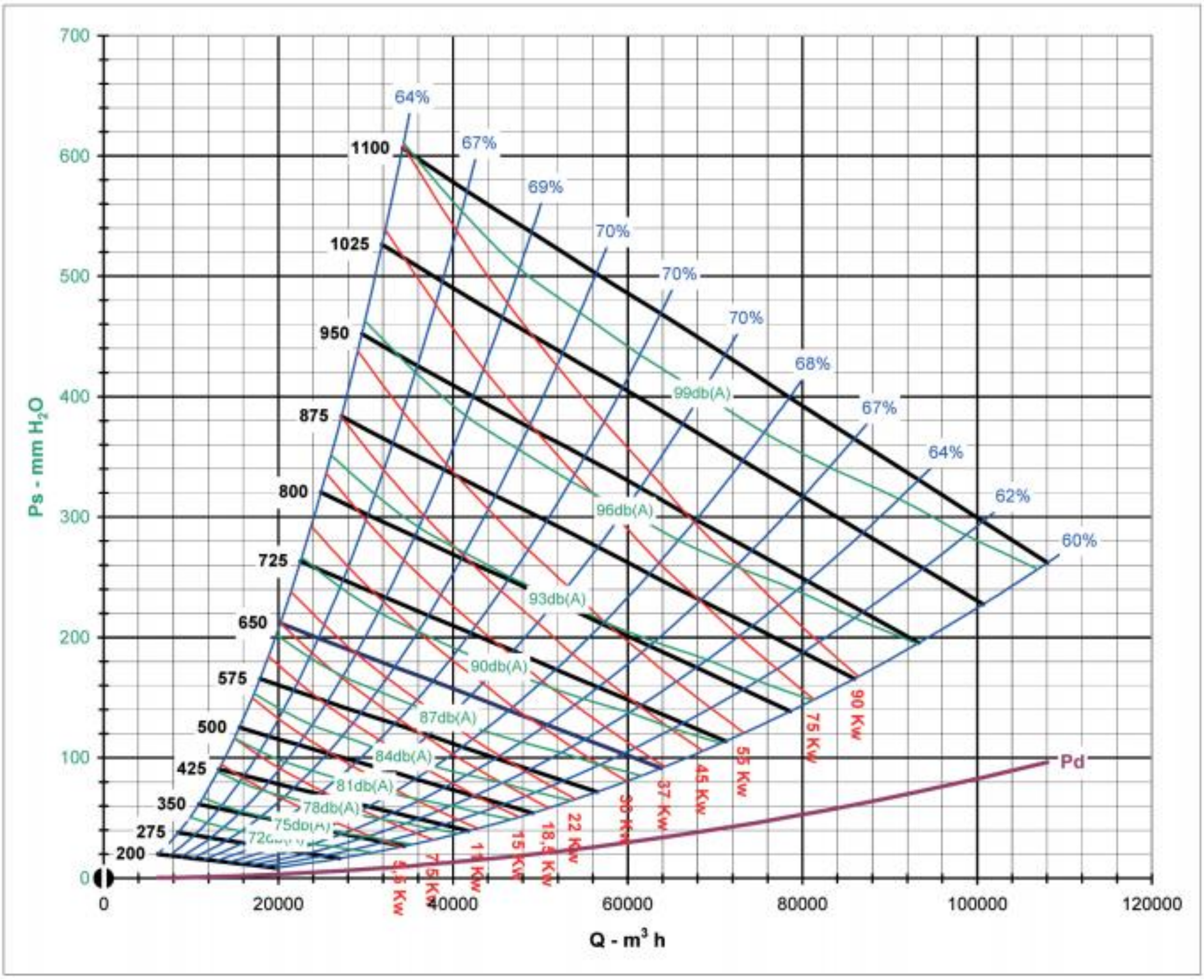


VENTILATORE Tipo	PTM	1450/33		ø girante	1460	standard
				altezza pala		standard

Fluido		Temp. di funz. °C	Altitudine m s.l.m.	Densità fluido
ARIA	Densità standard 1,293	21,1	0	1,200

Installazione di tipo B *

CURVA CARATTERISTICA ALLE CONDIZIONI DI FUNZIONAMENTO

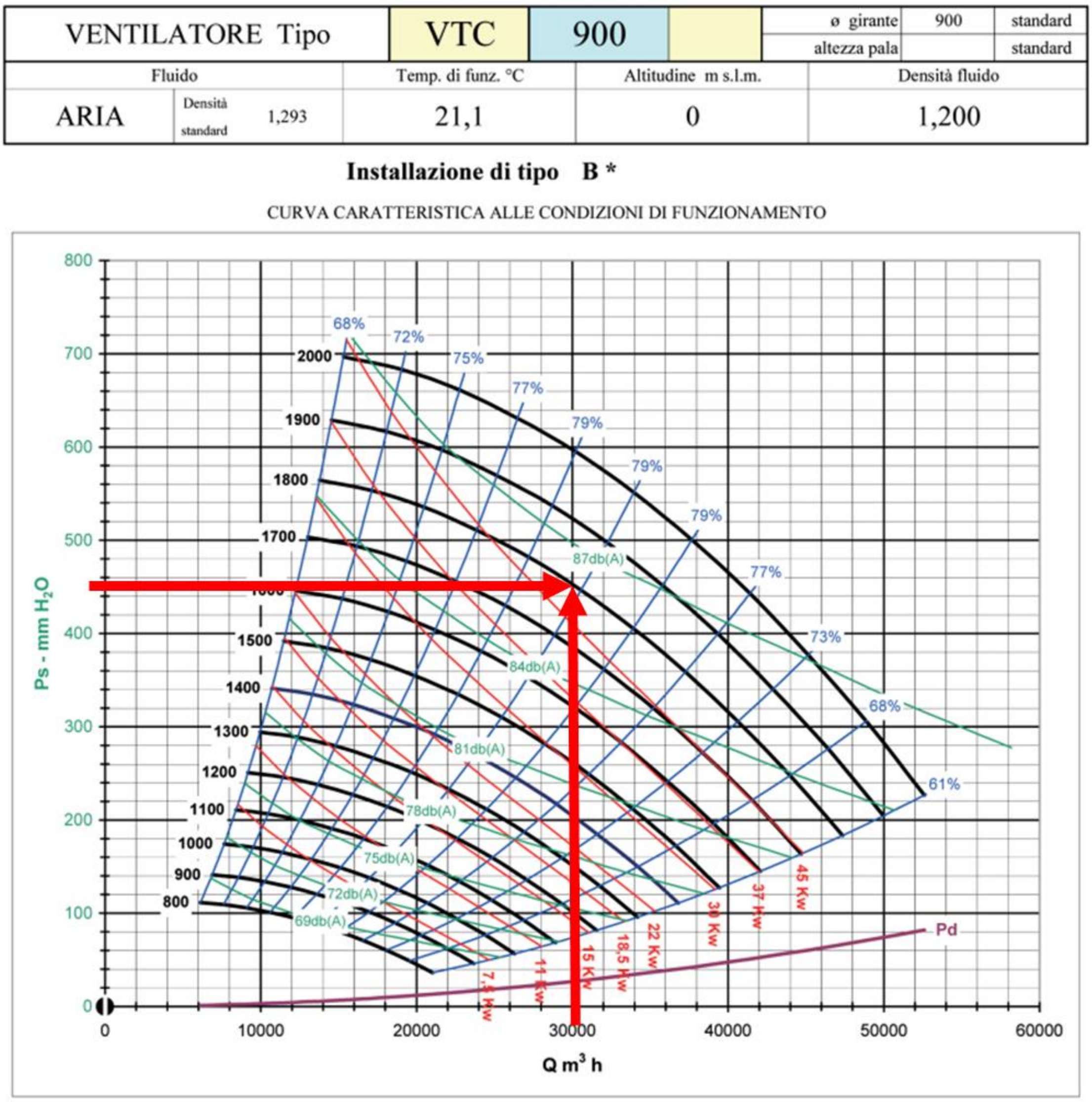


14.2.1 Solution

Project Flowrate at T = 120°C	Approximately30.000,00 m3/h
T	120°C
Static preassure	450 mm H_2O
Flowrate Features	Source of Polluted Gaseous Emissions: • Foundry, core-shooters • Foundry, pig-iron arc furnace Presence of • HCl • Ammines • Dust • Volatile Organic Compounds (BTEX, HCB)

Fan Model	VTC 900
Installed Power	≈ 45 kW

Mechanical Efficiency	79%
Propeller Material	AISI 316 (high temperature, presence of acids)
Casing Material	AISI 316 (high temperature, presence of acids)



VENTILATORE Tipo	VTC	900		ø girante	900	standard
				altezza pala		standard

Fluido			Temp. di funz. °C	Altitudine m s.l.m.	Densità fluido
ARIA	Densità standard	1,293	21,1	0	1,200

Installazione di tipo B *

CURVA CARATTERISTICA ALLE CONDIZIONI DI FUNZIONAMENTO

14.3. Static pressure

In order to design correctly a fan which of the following sentences is correct to define static pressure:
– Resistance to flow
– Equal in all directions
– Can be positive or negative
– Independent of air velocity

14.3.1 Solution

All the above sentences are true.

15. GENERAL DESIGN CONSIDERATION

15.1. Prevention or control measures?

A degreasing operation has been using organic solvent A, at a conveyor speed of 100 units/hr and a solvent temperature of 80°C that allows for maximum cleaning with minimum loss (lowest overall operating cost for the process).
A new regulation is passed requiring greatly reduced atmospheric emissions of solvent A. The process manager has several alternatives. You have to choose which of them can be considered a prevention measure (only one response is most correct).

- Reduce the T of the solvent. The conveyor speed must be slow down to get the same amount of cleaning. This may require the addition of another line.
- Change to another solvent having a lower vapor pressure (probably more expensive, but less organic matter would be emitted).
- Put in the necessary hooding, ducting, and equipment for a solvent recovery system which will decrease the atmospheric pollution and also result in some economic solvent recovery.
- Put in the necessary hooding, ducting, and equipment for a thermal oxidizing (afterburner) system which will burn the organic solvent vapors to a less polluting emission, but with no solvent recovery.

15.1.1 Solution

Change to another solvent having a lower vapor pressure (probably more expensive, but less organic matter would be emitted).

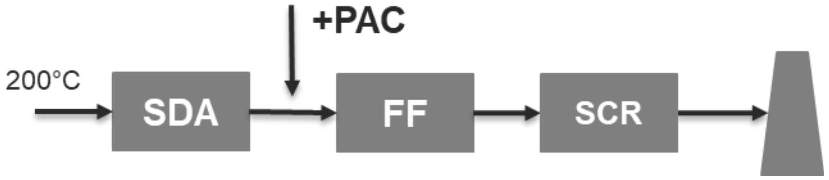
15.2. Energy consumption

All waste streams must be propelled through the control device and the associated ductwork and exhaust stack. Normally, this is done by means of a fan or blower.
We can reduce power demand (and thus operating costs) by:

- Increasing fan/blower efficiency
- Reducing the preassure drop
- Increasing the volume flow rate (Qin)

15.3. Units configuration in a MSWI

Considering a MSWI the following configuration of APC units can be considered correct? Why?



WHERE USED	

15.3.1 Solution

It is not correct because after a SDA the temperature is too low for an SCR.

15.4. Dry VS wet techniques

Both dry and wet techniques are used for the cleaning of the waste gases. Each technique, dry or wet, has its *advantages* and *disadvantages.* What are the most convenient techniques in order to :

a. achieve a higher emission temperature: dry / wet
b. keep higher the dew temperature: dry / wet
c. reduce the plume visibility (white plumes) in the wintertime: dry / wet
d. reduce the heat loss through the emitted waste gas: dry / wet
e. reduce chemical corrosion of ducts, APCDs and chimneys: dry / wet
f. remove acid gases from gas streams at ambient temperature: dry / wet
g. keep a lower gas flow (as a mass flow): dry / wet

15.4.1 Solution

h. achieve a higher emission temperature: **dry**
i. keep higher the dew temperature: **wet**
j. reduce the plume visibility (white plumes) in the wintertime: **dry**
k. reduce the heat loss through the emitted waste gas: **dry**
l. reduce chemical corrosion of ducts, APCDs and chimneys: **dry**
m. remove acid gases from gas streams at ambient temperature: **wet**
n. keep a lower gas flow (as a mass flow)?: **dry**

16. AIR MONITORING

16.1. Designing an air monitoring campaign?

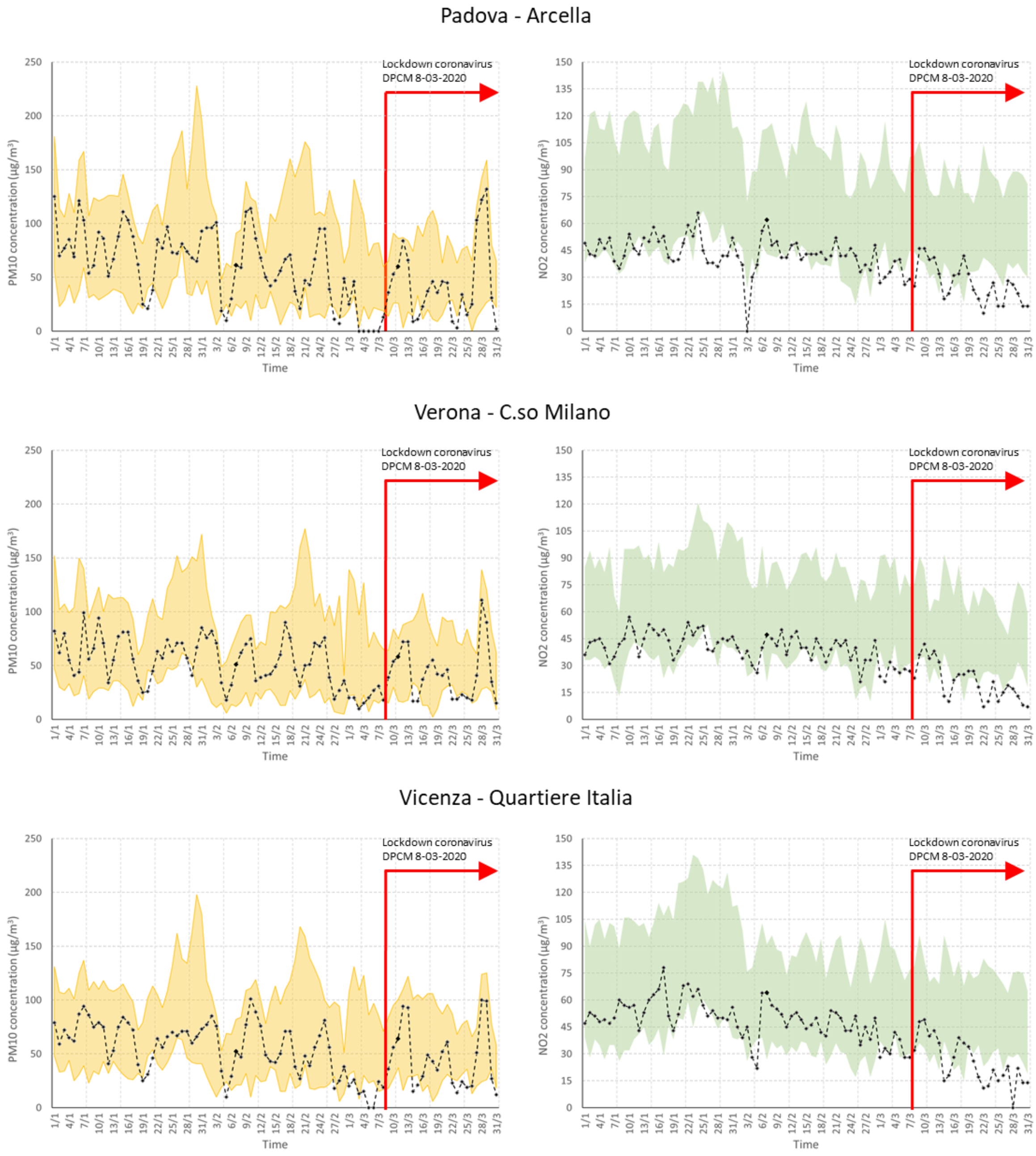
Which are the most important skills for designing and running an air monitoring campaign?

16.1.1 Solution

You must be able to select the right instrument, choosing the one that fit fine whith your purpose. Other important point are the selection of right place and season, in order to get the best analysis of air quality.
Moreover you must check that the instrument in use fit for the monitoring campaign and working properly.
Finally the researcher must be able to correctly interpret results

16.2. Exercise: Interpreting Air Monitoring Data

The lockdown coronavirus in Italy started officially on the 8-03-2020, but already a few days before the transport and industry activities had decreased. In some urban monitoring points, known to be very polluted areas, the concentrations of PM10 (µg/m3 at 293K, average daily value) and NO2 (µg/m3 at 293K, maximum hourly value) were measured during the lockdown. This data was compared with the range values of the previous 4 years during the same period.
Try to interpret the monitoring data represented in the following figure.



Legenda

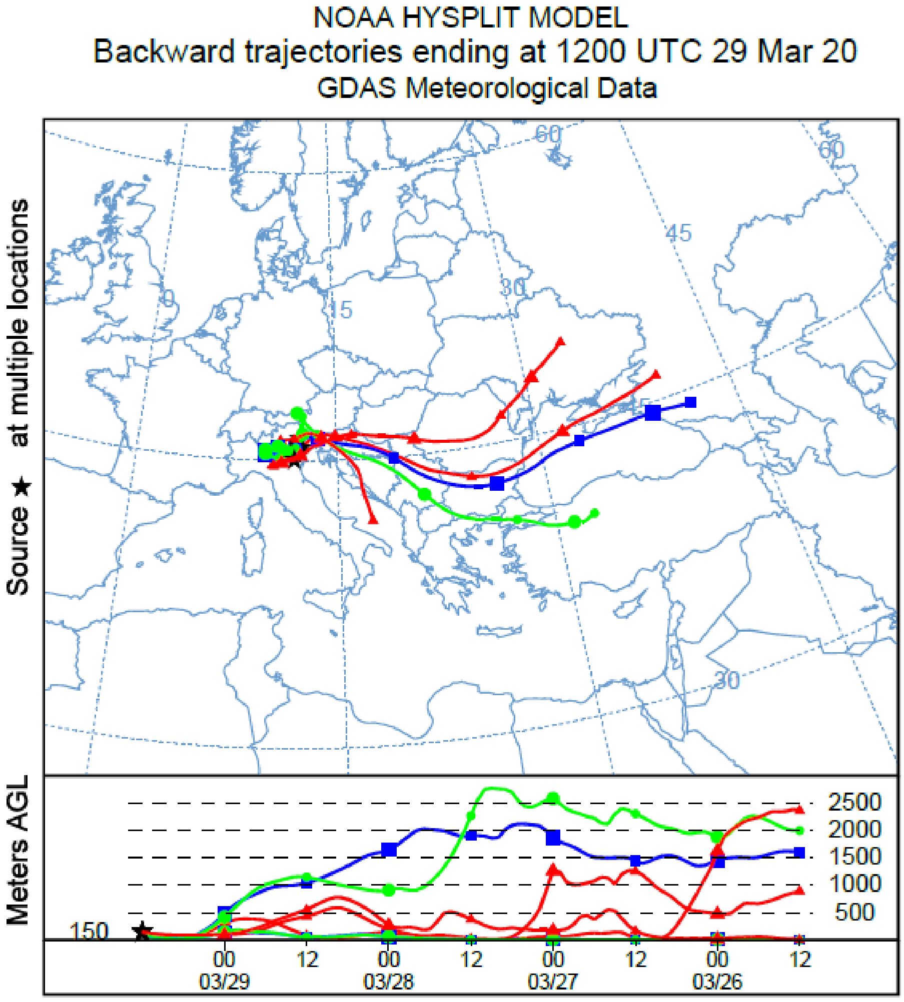
🟨 Range of concentration values (min-max) of PM10 (µg/m³ at 293K, average daily value) measured in the years 2016, 2017, 2018 and 2019. Monitoring time: 1st of January -31st of March (Reference: data from ARPAV)

🟩 Range of concentration values (min-max) of NO_2 (µg/m³ at 293K, maximum hourly value) measured in the years 2016, 2017, 2018 and 2019. Monitoring time: 1st of January -31st of March (Reference: data from ARPAV)

- ◆ - Concentration values of PM10 (µg/m³ at 293K, average daily value) or NO_2 (µg/m³ at 293K, maximum hourly value) measured in the year 2020. Monitoring time: 1st of January -31st of March (Reference: data from ARPAV)

16.2.1 Solution

The PM10 concentration parameter can also include the particulate matter of natural origin; therefore, even if the human activity ceases, the monitoring system can register peaks of concentrations due for example to sands from distant places (see figure below). That is what happened in the cited monitoring points.
The NO2 concentration, instead, is more correlated to human activity and in fact, decreases during the lockdown period.


NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 29 Mar 20
GDAS Meteorological Data
Source ★ at multiple locations
60
60
45
30
15
0
45
30
Meters AGL
2500
2000
1500
1000
500
150
00
03/29
12
00
03/28
12
00
03/27
12
00
03/26
12

17. SPECIAL TOPICS

17.1. Exercise: Unpleasant odour and virus diffusion in air from biological WWTP

Unpleasant odour and virus diffusion in air from biological WWTP can be strongly reduced through covering of primary treatment basins *(because of anoxic sewage*) extract the air and treat it.
To realize if the extracted air flow from such covered basins is sufficient – workers have to enter for regular inspection, you can

- Calculate the number of air changes per hour (= Air flow/Air volume) and compare it with published tables and/or other known plants (Y / N).
- Require continuous indoor monitoring of the concentrations of typical air pollutants (H_2S and NH_3): both personal and fixed monitoring systems(Y / N).

Sign if the previous sentences if they are correct (Y) or not (N).

- A higher number of air changes is required in summer or in winter? Explain why.

17.1.1 Solution

- Calculate the number of air changes per hour (= Air flow/Air volume) and compare it with published tables and/or other known plants: YES
- Require continuous indoor monitoring of the concentrations of typical air pollutants (H_2S and NH_3): both personal and fixed monitoring systems: YES
- A higher number of air changes is required in summer. Lower gas (H2S, RSH, NH3, …) solubility in water and faster anaerobic production due to reduced O_2 availability (*more request, but lower solubility*!); also, as temperature increases, the rates of chemical as well as biochemical reactions generally increase. This chemical phenomenon is referred to as Arrhenius behaviour. The same phenomenon also occurs with microorganisms and the myriad of chemical and biochemical reactions that constitute "microbial activity," but only to a point (this is why we storage food in refrigerators!). The resultis faster biological degradation of organic compounds (→ faster N-, S-gases production) due to > temperature! Beyond some optimum temperature, the activity of any organism declines.

17.2. Occupational exposure at WWTP

Frequent occupational exposure to raw sewage (e.g. biological WWTP *wastewater treatment plant*) is a significant risk factor for HAV (*hepatitis A virus*) infection. What prevention measures would you suggest in designing new WWTP? (select the correct measures from the following list).

a) build low depth basins (existing basins range in depth from 1.5 to 5.0 metres);
b) install submerged diffuse (fine bubbles) aeration systems;
c) install surface-aerated systems;
d) cover all the basins in the plant, extract the air and treat it.

17.2.1 Solution

The correct measures are:
b) install submerged diffuse (fine bubbles) aeration systems;
d) cover all the basins in the plant (but the final sedimentation basin), extract the air and treat it.

Note: Employees who are likely to be at risk of frequent exposure should have their immunity ensured. Personal protective equipment (PPE) *(Italian: DPI - Dispositivi di Protezione Individuale)* must be worn in designated area during O&M activities - Operation & Maintanance

17.3. Boiler fueled by natural gas

A 30 kW boiler fueled by natural gas, for use domestic heating (approximately an apartment up to 200 m^2).
Air composition: 79% N_2, 21% O_2.
Humidity of air is not considered (i.e. we consider that ambient air is dry air); if necessary, "MW" of air = 29;

Natural gas = Methane, CH_4; *LHV Lower Heating Value (or NHV Net Heating Value) of CH_4* (It.: potere calorifico inferiore, pci) = 50 MJ/kg.
Combustion process (to be balanced!): CH_4 (g) + O_2 (g) = CO_2 (g) + H_2O (g)
At maximum thermal capacity:

1) calculate the amount of methane required = ... kg/h (Nm^3/h);
2) calculate the amount of air required in the stoichiometric process = ...kg/h (Nm^3/h)
3) calculate the chemical composition of the wet flue gas under stoich. conditions: CO_2% = ..., H_2O% = ..., N_2%= ....;
4) calculate the amount of the wet flue gas emitted (under stoich. conditions) = ... Nm^3/h; ....m^3/h at 130 °C.
5) No fans are used for the extraction of the flue gas, that is only a natural draft occurs. A vendor claims that a stainless steel AISI 316L duct, Ø 80 mm, is suitable for the emission of the flue gas. What is your opinion? .... What is the calculated exit flue gas velocity? ..... m/s.
6) A condensing boiler extracts additional heat from the waste gases by condensing this water vapour to liquid water, thus recovering its latent heat of vaporization. Condensing boilers emit a visible plume of water vapour from the flue terminal (average flue temperature: 65 -70 °C). It is the responsibility of the installer to judiciously select a terminal location that does not cause a nuisance. The required flue pipe diameter would be > or < than that for common (non condensing boiler)?
7) If possible, compare the duct above with that of your domestic boiler.

17.3.1 Solution

Combustion process (to be balanced!): CH_4 (g) + 2 O_2 (g) = CO_2 (g) + 2 H_2O (g)
[Note: compare with condensing boilers!]
At maximum thermal capacity:

1) calculate the amount of methane required =30 kW/50 MJ/kg= 2.16 kg/h =0.135 Kmol/h =3.026 Nm^3/h
2) calculate the amount of air required in the stoichiometric process =3.026 *2*1/0.21= 28.8 Nm^3/h
3) calculate the chemical composition of the wet flue gas under stoich. Conditions. for each mole of oxygen in air, there exists 79/21 = 3.76 moles of nitrogen.
   Therefore, for each mole of methane we have 1 mole of CO_2; 2 moles of H_2O; 7.52 moles of N2; total moles=10.52
   CO_2% = 9.5 %, H_2O% = 19.0 %, N_2% = 71.5 %;
4) calculate the amount of the wet flue gas emitted (under stoich. conditions) =0.135 Kmol CH_4/h*10.52 mol Flue gas/ mol CH_4 *22.4 l/mol = 31.84 Nm^3/h → 47.0 m^3/h at 130 °C.
5) No fans are used for the extraction of the flue gas, that is only a natural draft occurs. A vendor claims that a stainless steel AISI 316L duct, Ø 80 mm, is suitable for the emission of the flue gas. What is your opinion? GOOD. AISI 316L has a good corrosion resistance to most chemicals, salts, and acids (also to marine environments). L = low carbon content.
   What is the calculated exit flue gas velocity? Using the current flow, the velocity is 2.6 m/s. The value of v is rather low, but this is a small emission source and we are using Natural Gas as a fuel; effective v, moreover, is higher than 2.6 because of air excess (e.g. 30 %) used in all combustion plants!.
6) In order to answer to the question. You have to consider that:
   - the temperature of flue gas from a condensing boiler is lowerthan from a non condensing boiler (65°-70° VS 130°C;
   - Some of the vapour water is converted into liquid to recover the latent heat of vaporization.
7) If possible, compare the duct above with that of your domestic boiler. Compare power and fuel duct diameters.