Design of Industrial Plants – Impianti Chimici, aa 2018/2019
Additional homeworks

a

A tank ($V = 15\ m^3$) containing methane ($M = 16\ kg/kmole$, viscosity $\mu = 1.1 \cdot 10^{-4} Pa \cdot s$) at initial pressure $p_0 = 20 \cdot 10^5 Pa$ and temperature $T = 293\ K$ is connected with a valve V to a pipe ($L = 500\ m$, $D = 0.1\ m$) and a burner working at atmospheric pressure. The valve is initially closed.

1. Calculate the gas mass flow rate fed to the burner when the valve opens (assume isothermal flow along the pipe and friction factor $f = 0.003$);
2. Calculate the time necessary to halve the pressure in the tank;
3. Calculate the amount of gas delivered by the tank up to that time.

b

In a plant for bio-diesel production a shear sensitive fluid ($\rho_L = 900\ kg/m^3$, $\mu = 1.8 \cdot 10^{-3} Pa \cdot s$) is to be fed to a reactor without using a pump. Reactor loading can be performed in 3 hours feeding a constant fluid flow rate $Q_L = 8\ L/s$ from a tank B using a pipeline ($L_2 = 20\ m$, $D_2 = 0.1\ m$). The feeding system designed by the plant engineer to feed the shear sensitive fluid works as follows: the fluid stored in tank B, very large, is pressurized delivering gas from tank A to B using a pipeline ($L_1 = 30\ m$, $D_1 = 0.1\ m$) equipped with a valve V1. Tank A is fed by a compressor which maintains a constant value of pressure in A during tank B loading. After loading (valve V1 closed), the flow rate of shear sensitive fluid delivered by tank B can be modulated continuously using a valve V2 to maintain a constant value of Q_L toward the reactor. Assuming smooth pipes and isothermal flow ($T = 25^oC$) for the gas (air, $M = 29\ kg/kmole$, $\mu = 1.8 \cdot 10^{-5} Pa \cdot s$),

1. Calculate the minimum value of pressure in tank B which allows to deliver the flow rate Q_L;
2. Calculate the value of pressure in tank B when the valve V2 opens (volume occupied by the gas equal to $10\ m^3$);
3. Calculate the value of pressure in tank A required to transfer a constant flow rate of gas from A to B;
4. Calculate the mass flow rate delivered by the compressor to maintain tank A pressurized during the gas loading of tank B.

c

A pipeline transporting methane ($M = 16\ kg/kmole$, $\mu = 1.2 \cdot 10^{-5} Pa \cdot s$) from Russia to Italy is composed of segments of pipe ($L = 180\ km$, $D = 1.m$) with re-compression stations in-between. At Malborghetto, the first re-compressing station within the Italian boundary, a measure is made for pressure and flow rate downstream the re-compressing station. The flow rate, measured at 0^oC and $1\ atm$, is $Q = 300,000\ m^3/h$ whereas the pressure is $P_1 = 30\ atm$.

1. Assuming isothermal flow along the pipeline ($T = 25^oC$) and smooth pipeline (Blasius law for the friction factor), calculate the pressure expected at the end of the pipeline segment, upstream of the next re-compression station of Istrana;
2. Due to a larger demand of gas from Italy, Russians claim they trebled the flow delivered to Italy. In this condition, Italian engineers measure an 80% reduction of pressure at the end of the pipeline segment (Istrana). Check if the Russian claim is supported by the measure of pressure and calculate the real flow rate variation if different from the one claimed.
3. Under standard operating conditions (point 1) the pipeline control system should be able to detect gas leakages by monitoring the variation of pressure at the downstream section of the pipe. Assuming that there is a leakage through a hole (section $A = 10\ cm^2$) located 100 km downstream of Malborghetto, calculate the mass flow rate of gas lost and the variation of pressure detected at Istrana (assume adiabatic flow, $\gamma = 1.3$, for the gas leaking from the pipe).

d

In an industrial plant, a burner fed with methane ($MM = 16\ kg/kmole$, $\mu = 1.37 \cdot 10^{-5} Pa \cdot s$) is used to heat the diathermic oil used as heat transfer fluid used for vapor production. The closed loop of diathermic oil ($\rho_{oil} = 800\ kg/m^3$, $\mu_{oil} = 0.008\ Pa \cdot s$) is composed of a pump and a pipeline ($D = 0.05\ m$, $L = 500\ m$) connecting the heat transfer coil placed inside the burner with the evaporator and back path.

1. Considering that the flow rate of oil circulating in the coil is $Q = 2\ L/s$, calculate the power of the pump to be installed in the loop if the pressure loss through the coil and evaporator are equal to $\Delta p = 4\ atm$;

2. The gas fed to the burner is stored in a tank ($V = 300\ m^3$) designed for maximum storage pressure equal to 20 atm. Assuming a tank temperature $T = 20^oC$, calculate the maximum amount of methane which can be stored;

3. From the tank, the gas is fed to the burner at a constant mass flow rate $\dot{m} = 0.025\ kg/s$ using a pipeline ($d = 1\ cm$, $L_b = 20\ m$) equipped with a valve used to modulate the flow. Assuming isothermal transport, calculate the pressure loss (as equivalent pipe diameters) which should be induced by the valve when the tank is full of gas;

4. Calculate the minimum value of pressure inside the tank required to deliver the desired flow rate and the time spent before subsequent gas refills.

e

In a plant for the synthesis of UF resins the heat of the exothermic reaction is used to produce overheated ($T = 700\ K$) water vapor ($MM = 18\ kg/kmole$, $\mu = 2.8 \cdot 10^{-5} Pa \cdot s$) at $p = 15\ bar$ pressure. Water vapor is transferred from the batch reactors used for the synthesis of resins (point A) to a different point in the plant (B) where the vapor can be spilled, using a pipeline ($D = 0.1\ m$, $L = 500\ m$).

1. Assuming isothermal transport for the gas along the smooth pipe AB, calculate the value of pressure in B if the mass flow rate transferred from A to B is $\dot{m} = 3\ kg/s$;

2. Check if the flow is sonic if B is the end point of the line, open to the atmosphere;

3. From point B, the vapor can be fed alternatively toward two different points of use, C and D. Assuming that the pipelines toward points C and D have diameter equal to $D_C = 0.15\ m$ and $D_D = 0.05\ m$ and that the pipes end sections are at atmospheric pressure, check if the flow is sonic along the two lines;

4. Calculate the length of the pipes BC e BD.

f

Due to the unwise maneuver of a driver, a tanker truck ($V = 130\ m^3$) trapped under an underpass, causing the leakage of methane ($MM = 16\ kg/kmole$, $\mu = 2 \cdot 10^{-5} Pa \cdot s$). Assuming that the pressure inside the tank is initially equal to $p_0 = 10\ atm$ and the temperature is $T = 25^oC$:

1. Check if the flow is sonic (assume adiabatic transformation for the gas, $\gamma = 1.3$);

2. Calculate the mass flow rate exiting at starting time if the leaking hole equivalent diameter is $d_e = 1\ cm$;

3. Calculate how long sonic flow conditions can be sustained;

4. Calculate the amount of gas leaked from the tank when the pressure in the tank reaches 9 atm;

5. The rapid reaction of the fire department allowed to seal the leakage and to transfer the gas into a different tanker truck using a pipeline ($L = 30\ m$, $d = 3\ cm$). Check if the flow to the second tank is sonic (assume isothermal flow at $T = 25^oC$ and $f = 0.003$);

6. Calculate the flow rate of gas delivered to the second tank when the siphoning starts.

g

A pipeline ($D = 5\ cm$, $L = 300\ m$) is used to deliver a mass flow rate of oxygen ($MM = 32\ kg/kmole$, $\mu = 2. \cdot 10^{-5} Pa \cdot s$) equal to $w = 0.80\ kg/s$ from tank A to tank B.

1. Assuming that tank be is maintained at atmospheric pressure, the pipe is smooth and gas transformation is isothermal ($T = 298\ K$), check if the flow is sonic at the pipe outlet;

2. Calculate the pressure in tank A required to transfer the design gas flow rate. Use Blasius law to calculate the pipe friction factor.

3. Calculate the mass flow rate leaking from tank A if, for accidental reasons, a hole ($d = 2\ cm$) is produced in the tank. Assume adiabatic flow ($\gamma = 1.4$).

h

In a plant, a large tank A fed by a line equipped with a valve V1 is connected by a valve V2 to a smaller tank B from which the gas can be delivered to a point C using a pipeline BC equipped at its upstream section with a valve V3. Tanks volumes are $V_A = 20\ m^3$ and $V_B = 1\ m^3$; they are filled with air ($MM = 29\ kg/kmole$, $\mu = 1.8 \cdot 10^{-5} Pa \cdot s$, $T = 25^oC$) at atmospheric pressure and all valves are closed. At starting time, valve V1 (pipeline diameter $D = 0.1\ m$) opens and tank A is filled by a constant specific flow rate $G = 1.3\ kg/m^2s$. Assuming isothermal transformation for the gas:

1. Calculate the time required to raise the pressure in A to 20 atm;
2. At this condition, valve V1 closes and valve V2 connecting A to B opens; considering that the pipeline AB is negligible in length, calculate the specific mass flow rate G_1 delivered from A to B when V2 opens;
3. Calculate the value of pressure in B at the end of gas transfer;
4. After the filling of tank B, V2 is closed and V3 partially opens. Specifically, the valve opening is modulated to guarantee a constant flow rate equal to the minimum critical flow rate from B to C. Assuming that point C is at atmospheric pressure, $L_{BC} = 100\ m$, $D_{BC} = 0.02\ m$, calculate the pressure loss (as equivalent lengths of pipe) induced at starting time by valve V3;
5. Calculate how long the minimal sonic flow rate can be delivered from tank B to C.

j

In a painting plant, nitrogen ($MM = 28\ kg/kmole$, $\mu = 1.78 \cdot 10^{-5} Pa \cdot s$) is used as atomizing gas for the spray painting guns. The tank A of the painting division ($V_A = 5\ m^3$) is refilled from the storage tank B (larger than A) which is maintained at constant pressure $p_B = 25\ atm$. The pipeline connecting B to A is characterized by $L = 50\ m$ and $D = 0.05\ m$.

1. Calculate the gas flow rate transferred along the pipeline when the valve between the tanks opens (initial pressure inside tank A is atmospheric); assume isothermal transformation for the gas ($T = 293\ K$) and friction factor $f = 0.003$;
2. Calculate the mass transferred from B to A to raise p_A up to 15 atm;
3. If the valve connecting B to A is left open, the pressure in A can raise up to a maximum of 20 atm before the breaking of a rupture disk ($d = 2.5\ cm$). Calculate if, in case of disk breakage, the flow of nitrogen exiting from the tank is sonic.
4. Calculate how long the sonic flow is maintained if the valve connecting B to A is closed.

k

A pipeline transporting methane ($MM = 16\ kg/kmole$, $\mu = 2.1 \cdot 10^{-5} Pa \cdot s$) is composed of segments of pipe ($D = 0.4\ m$, $L = 200\ km$) with re-compressing/refrigerating stations in between where the gas pressure is raised up the value required to transfer the gas.

1. Calculate the suction pressure of the compressor when the gas flow rate, evaluated at atmospheric pressure and $T = 293\ K$, is $Q = 12000\ m^3/h$ assuming smooth pipe, isothermal transport for the gas ($T_g = 280\ K$) and pressure at the compressor outlet equal to 6 atm;
2. Calculate the power of the compressor if the gas transformation inside the compressing unit can be considered adiabatic and reversible ($\gamma = 1.4$);
3. Calculate the mass flow rate leaking from the pipeline if, for accidental reasons, a hole is produced in the pipeline (hole section 1 cm^2), 1 km downstream the recompression station (assume adiabatic flow from the leakage).

l

The compressed air delivering system of an industrial plant is composed of a compressor sucking air ($MM = 29\ kg/kmole$, $\mu = 1.8 \cdot 10^{-5} Pa \cdot s$) from the environment, a storage tank A ($V_A = 20\ m^3$) and a distributing tank B ($V_B = 2\ m^3$). Tanks A and B are connected by a pipeline AB ($L_{AB} = 200\ m$, $D_A = 3\ cm$). A second pipeline connects tank B ($L_{BC} = 20\ m$, $D_B = 6\ cm$) with point C (end-use point of compressed air, at p_{atm}). Assuming that the system delivers a mass flow rate $\dot{m} = 0.3\ kg/s$, that the transport is isothermal ($T = 25^oC$) and the pipelines are smooth (use Blasius law to calculate the friction factors),

1. Check if the flow from tank B to point C is sonic;
2. Calculate the pressure in tank B;
3. Calculate the pressure in tank A and the flow rate delivered by the compressor if the system is working at steady state conditions.

m

The compressed air delivering system of an industrial plant is composed of a compressor sucking air ($MM = 29\ kg/kmole$, $\mu = 1.8 \cdot 10^{-5} Pa \cdot s$) from the environment, a storage tank A ($V_A = 25\ m^3$) and a distributing tank B ($V_B = 4\ m^3$). Tanks A and B are connected by a pipeline AB ($L_{AB} = 300\ m$, $D_A = 4\ cm$). A second pipeline connects tank B ($L_{BC} = 30\ m$, $D_B = 8\ cm$) with point C (end-use point of compressed air, at p_{atm}). Assuming that the system delivers a mass flow rate $\dot{m} = 0.4\ kg/s$, that the transport is isothermal ($T = 25^oC$) and the pipelines are smooth (use Blasius law to calculate the friction factors),

1. Check if the flow from tank B to point C is sonic;
2. Calculate the pressure in tank B;
3. Calculate the pressure in tank A and the flow rate delivered by the compressor if the system is working at steady state conditions.

n

A screw volumetric compressor is used to refill with compressed air ($MM = 29\ kg/kmole$) a storage tank A ($V_A = 2\ m^3$). During the loading stage, environmental air ($T = 20^oC$) is sucked by the compressor, raised in pressure and refrigerated up to $T_A = 60^oC$ to be stored in the tank. The mass flow rate processed by the compressor is $\dot{m} = 0.04\ kg/s$; the pressure in the tank raises from $p_{A,0} = 1\ atm$ to a maximum of 8 atm.

1. Calculate the time necessary to fill the storage tank;
2. Assuming that the compression stage can be represented as an ideal reversible adiabatic transformation for the gas ($p/\rho^\gamma = cost$, $\gamma = 1.4$) followed by isobaric cooling, calculate the maximum power of the compressor to be installed to load the tank (diameter of suction and delivery pipes is $d = 3\ cm$);
3. The tank is connected through a valve V2 to a pipeline for the end-use delivery of compressed air ($L_2 = 50\ m$, $d_2 = 2\ cm$). Assuming isothermal flow along the line and smooth pipe ($f = 0.003$), check if the flow is sonic/non sonic and calculate the mass flow rate transferred from the tank when valve V2 opens;
4. When necessary, the tank can be rapidly emptied using a nozzle ($L_1 = 0.2\ m$, $d_1 = 1\ cm$) opening valve V1. Assuming isothermal flow through the nozzle and $f = 0.003$, check if the flow is sonic/non sonic and calculate the mass flow rate exiting from the nozzle when valve V1 opens.

o

In a steelmaking plant, the system used to deliver methane ($MM = 16\ kg/kmole$, $\mu = 2.2 \cdot 10^{-5} Pa \cdot s$) to a nozzle for melting the metal scrap is composed of a main tank A ($V_A = 60\ m^3$) located outside the plant, and a secondary tank B ($V_B = 10\ m^3$) used to feed the nozzle. The two tanks are connected by a pipeline A-B ($L_{AB} = 300\ m$, $D = 5\ cm$) equipped with a valve V1. The starting values of pressure inside the tanks are $p_A = 30\ atm$ and $p_B = 1\ atm$. Gas transfer from tank B to the nozzle along a distribution line ($L = 30\ m$, $d = 2.5\ cm$) is modulated using a valve V2. Assuming isothermal flow for the gas ($T = 25^oC$) and smooth pipes ($f = 0.003$)

1. Calculate the mass flow rate transferred at starting time from tank A to tank B when valve V1 opens (V2 is closed);
2. Calculate the pressure in the two tanks when gas transfer from A to B stops (V2 still closed);
3. Calculate the pressure drop (as equivalent length of pipe) due to V2 if the mass flow rate transferred from B to the nozzle is maintained equal to $\dot{m} = 0.15\ kg/s$ to guarantee the complete combustion of methane;
4. During scrap melting, the valve V2 is progressively opened to guarantee a constant flow rate of methane ($\dot{m}$). Calculate the minimum value of pressure in tank B which allows to deliver the target flow rate and the time after which tank B should be refilled.

p

A firm designing wastewater treatment systems for the surface run-off from industrial courts should design a plant able to collect sand particles and oil droplets entrained by rainwaters ($Q = 3\ L/s$). The plant is composed of a number of standard size settling/flotation chambers ($L = 3\ m$ long, $W = 1\ m$ wide and $H = 1.5\ m$ deep).

1. Calculate how many settling/flotation chambers should be installed in parallel to separate with 90% efficiency oil droplet ($\rho_{oil} = 800\ kg/m^3$) of size $D_o = 100\ \mu m$.
2. Calculate the separation efficiency of the system if the particle size distribution for sand and oil droplets is the one in Table.

Sand		Oil	
$\rho_s = 2000\ kg/m^3$		$\rho_o = 800\ kg/m^3$	
$D_p.\ [\mu m]$	$m_p,\ [mg]$	$D_0.\ [\mu m]$	$m_p,\ [mg]$
50	325	50	0.50
100	450	100	1.0
150	225	200	0.20

q

A tank ($V = 10\ m^3$, $T = 20^oC$ and initial $p_0 = 10\ atm$) contains methane ($MM = 16\ kg/kmole$). The tank is equipped with a safety valve V1 ($d = 2\ cm$) and is connected through a valve V2 to a pipe ($L = 250\ m$, $D = 2.5\ cm$) open to the atmosphere. At starting time V1 is open and V2 is closed. Assuming isothermal transformations for the gas,

1. Check if the flow of methane exiting from the safety valve is sonic (assume $f = 0.003$);
2. After 40 s valve V1 is closed and valve V2 opens. Calculate the mass of gas exited from the tank during this period;
3. Calculate the gas flow rate delivered through valve V2.

r

In a biomass burning plant a plate-plate ESP is used to collect the fines produced by the combustion process. ESP's dimensions are $H = 2\ m$, $W = 0.8\ m$ and $L = 4\ m$ and the ESP is composed of 5 plates, 2 maintained at high potential and 3 grounded. The gas flow rate is $Q = 2.5\ m^3/s$ ($\mu = 2.1 \cdot 10^{-5} Pa \cdot s$).

1. Given a collection efficiency equal to $\eta = 95\%$ for particles with $D_p = 5\ \mu m$, and given charge surface density $\sigma = 7.64 \cdot 10^{-7} C/m^2$, calculate the voltage of the high potential plates;
2. Calculate the global collection efficiency if the particle size distribution of dusts in the flow is the one reported in Table.

$D_p,\ [\mu m]$	1.	2.5	5.	10.
$f(D_p),\ [\%]$	5	30	20	45

3. Due to the increasing level of pollution in the industrial area, the supervisory authority imposed to revamp the plant to improve the particle collection efficiency. The engineer in charge for plant revamping proposed two design alternatives not entailing excessive costs since they require to buy an extra collecting plate ($L \times H$):
   - Alternative A: re-positioning of collecting plates to build a particle collection system composed of 3 plates ($W = 0.4\ m$) twice longer ($L = 8\ m$) than before, connected to the tension already available in the plant;
   - Alternative B: re-positioning of collecting plates to build a particle collection system composed of 6 plates ($W = 0.8\ m$) having the same volumetric envelope ($L = 4\ m$) and using the same tension available in the plant;

   Check which of the two alternatives is the most effective to improve the collection efficiency for 5 μm particles.

s

The Research & Development department of a firm producing fireplaces is developing a new particle abatement system to contain dust emissions. The system is composed of a Lapple type cyclone, working as a pre-separator for the larger size particles, and an ESP in series. Considering that the flow rate to be processed (air, $MM = 29\ kg/kmole$, viscosity $\mu = 1.8 \cdot 10^{-5} Pa \cdot s$) is $\dot{m} = 0.010\ kg/s$, smoke temperature is $T = 150^oC$, pressure is atmospheric and dust characteristics are: density, $\rho_p = 300\ kg/m^3$, and particle size distribution given in Table,

1. Using the practical design equation for cyclones, calculate the global collection efficiency of the pre-separator if the cyclone diameter is $D_c = 20\ cm$;
2. Calculate the tension to be used for the high potential electrode of a tubular ESP ($D = 2R = 15\ cm$, $L = 50\ cm$) to collect 99% of particles with diameter equal to $D_p = 1\ \mu m$ (assume tabulated values for the electric charge acquired by the particles and an average electric flow field equal to $E = V/R$);
3. Calculate the overall collection efficiency for the two-stage system.

D_p. [μm]	%	q_p, [C]
0.1	5	$2.4 \cdot 10^{-20}$
1.0	30	$2.4 \cdot 10^{-18}$
5.0	20	$6.0 \cdot 10^{-17}$
10.0	45	$2.4 \cdot 10^{-16}$

t

The screw volumetric compressor installed in a lab is used to compress and stock environmental air into a tank ($V = 1\ m^3$). A pipeline ($L = 40\ m\ d = 2\ cm$) connected to the tank is used to deliver compressed air ($\mu = 1.8 \cdot 10^{-5} Pa \cdot s$) to the end-use point. Assuming isothermal flow transformation for the gas ($T = 25^o C$) and smooth pipe ($f = 0.003$), calculate:

1. The amount of air transferred inside the tank if, starting from atmospheric pressure with the delivering line closed, the compressor feeds air to the tank at a flow rate $\dot{m} = 0.12\ kg/s$ until the pressure in the tank raises to 8 atm;
2. Calculate the time necessary to load the tank;
3. After loading, the compressor powers off and the delivery line is opened to feed compressed air: calculate the maximum mass flow rate $\dot{m}_{max}$ which can be delivered by the system;
4. Calculate which is the threshold value of pressure in the tank to power on the compressor to prevent the reduction of delivered mass flow rate below $0.7 \cdot \dot{m}_{max}$;
5. Calculate the pressure in the tank at steady state if the compressor is always powered on.

u

In a biomass burning plant a cyclone is used to separate the fines generated by the the combustion process. The smoke flow rate ($MM = 29\ kg/kmole$, $\mu = 2 \cdot 10^{-5} Pa \cdot s$) is $Q = 4250\ Nm^3/h$. Smoke temperature is $T = 200^o C$ and dust density is $\rho_p = 800\ kg/m^3$.

1. Calculate the volumetric flow rate of smoke;
2. Size a Swift type cyclone to collect $D_p = 10\ \mu m$ particles with $\eta = 90\%$ efficiency (assume $m = 0.55$);
3. Calculate the pressure drop and the power required to feed the flow through the cyclone;
4. Calculate the overall collection efficiency if the particle size distribution of dusts in the smoke is that given in Table.

D_p, [μm]	2.5	5.0	10.0	15.0
$f(D_p)$, [%]	15	20	50	15

v

Spherical pellets of catalyst ($D_p = 100\ \mu m$, $\rho_p = 300\ kg/m^3$) are used to promote a polymeric reaction in the gas phase in a floating bed reactor. Assuming that the spherical pellets move in the Stokes regime,

1. Calculate the gas flow velocity ($\rho_g = 1.4\ kg/m^3$, $\mu_g = 1.8 \cdot 10^{-5} Pa \cdot s$) to maintain the pellets stably suspended inside the reactor (reactor cross section equal to $A = 1\ m^2$);
2. When the catalyst de-activates, the pellets should be removed from the reactor to be regenerated. In this stage, the gas flow rate fed to the reactor is doubled to transfer the pellets inside a Swift type cyclone where they can be separated from the gas. Size the Swift cyclone to collect pellets with at least 98% efficiency.
3. Calculate the pressure drop through the cyclone.

w

The settling tank of a sludge treatment plant should be sized to process a flow rate $Q = 100\ L/s$ of water containing suspended solids ($D_{p,eq} = 30\ \mu m$, $\rho_p = 1200\ kg/m^3$). The fingerprint available for the settling tank in the plant layout is an area $A_{max} = 20\ m^2$. The plant manager's request is a target separation efficiency $\eta \geq 95\%$.

1. Check if it is possible to satisfy the target on collection efficiency given the constraint imposed on the maximum fingerprint in plant layout;

2. The process engineer suggests to use a flocculating agent to promote the aggregation of suspended solids into flocs whose size is larger than 30 μm. Calculate how large should be the flocs to settle down inside the settling chamber.

3. Discuss any alternative solution which could be adopted to achieve the target separation efficiency given the constraints imposed.

x

The settling tank installed in an industrial wastewater treatment plant is designed to separate suspended solids and oil droplets from process water. The surface of the settling tank ($W \cdot L$) is 20 m^2 and the tank is $H = 0.5\ m$ deep. The water flow rate to be processed is $Q = 0.04\ m^3/s$ and contains suspended solids ($D_p = 100\ \mu m$, $\rho_p = 2000\ kg/m^3$) and oil droplets ($D_o = 120\ \mu m$, $\rho_o = 500\ kg/m^3$).

1. Discuss if it is relevant or not to know tank's dimensions W and L;

2. Calculate the collection efficiency for the solid and the oil phases (assume Stokes regime for suspended particles and droplets);

3. Due to the extension of the industrial plant, the flow rate to be processed doubles with a consequent deterioration of the separation performances. Calculate the new values of collection efficiencies for the solid and oil phases.

4. The plant engineer proposes the installation of a multi-plate coalescer in the downstream portion of the settling tank (10% of the tank footprint). Calculate the distance between planes in the multi-plate coalescer to achieve the same separation efficiency for oil droplets as before plant extension.

z

An underground settling/flotation tank is used to treat rainwaters ($\rho = 1000\ kg/m^3$, $\mu = 1 \cdot 10^{-3} Pa \cdot s$) drained from a parking area. Tank sizes are the following: length $L = 6\ m$, height $H = 2\ m$ and width $W = 2\ m$.

1. Considering that $\rho_{oil} = 800\ kg/m^3$ and the maximum flow rate of water to be processed is $Q = 3\ L/s$, calculate the separation efficiency for oil droplet with $D_o = 100\ \mu m$;

2. During plant revamping, the duct used to feed rainwaters to the tank has been resized (reduced in diameter). As a consequence, the shear rate on the oily phase increased determining a finer fragmentation of the oil droplets at the inlet of the tank ($D_o = 20\ \mu m$). Calculate the new value for the oil separation efficiency.

3. To achieve the original target separation efficiency ($\eta \geq 98\%$) for the smaller oil droplets the designer proposes the installation of a multi-plate coalescer inside the tank (length $L' = 0.5\ m$). Calculate the distance between plates to achieve the target collection efficiency ($\eta = 98\%$ for $D_o = 20\ \mu m$).

4. Calculate the pressure drop associated to the installation of the coalescer.

aa

A Stairmand type cyclone is used to separate wood fibers from a gas stream. Considering that particle and gas characteristics are: density, $\rho_p = 300\ kg/m^3$, diameter $D_{p,eq} = 100\ \mu m$, gas flow rate, $\dot{m} = 150000\ kg/h$, density $\rho = 0.9\ kg/m^3$, viscosity $\mu = 1.8 \cdot 10^{-5} Pa \cdot s$, temperature $T = 20^oC$,

1. Using the practical design equations for the sizing of cyclones, calculate the cyclone diameter to have $\eta = 99\%$ per $D_p = 100\ \mu m$ particles (assume $m = 0.75$);

2. Calculate the power of the compressor required to feed the flow through the cyclone;

3. Calculate the overall collection efficiency for the particles if their particle size distribution is the one summarized in Table.

D_p, $[\mu m]$	1	5	10	50	100	150
$f(D_p)$, [%]	5	10	20	30	20	15

bb

Flue gases from an industrial burner (flow rate $Q = 2\ m^3/s$, $MM = 29\ kg/kmole$, $p = 1\ atm$, $T = 100^oC$, $\mu = 1.8 \cdot 10^{-5} Pa \cdot s$) contain fly ashes ($\rho_p = 500\ kg/m^3$). The authorization for plant operation prescribes the installation of a flue gas treatment system to collect 98% of the particles with $D_p = 100\ \mu m$. Two different projects have been proposed for the treatment system: the first includes the installation of a settling chamber ($L = 5\ m$, $H = 2\ m$, $W = 2\ m$) and a Swift type cyclone; the second includes the installation of a battery of 20 cyclones (Swift type).

1. Calculate the separation efficiency of the settling chamber and of the cyclone (project 1):
2. Using the practical design equations for the design of cyclones, calculate the size of the cyclone (assume $m = 0.7$) and the overall pressure drop for the flue gas treatment system of project 1;
3. Using the practical design equations for the design of cyclones, calculate the size of the cyclones of the battery(assume $m = 0.59$) and the pressure drop for project 2;
4. Discuss which of the projects proposed is the most attractive.

cc

Flue gases from an industrial burner (flow rate $Q = 3\ m^3/s$, $MM = 29\ kg/kmole$, $p = 1\ atm$, $T = 100^oC$, $\mu = 1.8 \cdot 10^{-5} Pa \cdot s$) contain fly ashes ($\rho_p = 600\ kg/m^3$). The authorization for plant operation prescribes the installation of a flue gas treatment system to collect 98% of the particles with $D_p = 80\ \mu m$. Two different projects have been proposed for the treatment system: the first includes the installation of a settling chamber ($L = 6\ m$, $H = 3\ m$, $W = 3\ m$) and a Swift type cyclone; the second includes the installation of a battery of 40 cyclones (Swift type).

1. Calculate the separation efficiency of the settling chamber and of the cyclone (project 1):
2. Using the practical design equations for the design of cyclones, calculate the size of the cyclone (assume $m = 0.7$) and the overall pressure drop for the flue gas treatment system of project 1;
3. Using the practical design equations for the design of cyclones, calculate the size of the cyclones of the battery(assume $m = 0.57$) and the pressure drop for project 2;
4. Discuss which of the projects proposed is the most attractive.

dd

An oil separation system is composed of a flotation chamber and a coalescing filter. Considering that the flotation chamber is $W = 1\ m$ wide, $H = 1\ m$ high and $L = 4\ m$ long and that the flow rate to be processed is $Q = 5\ L/s$,

1. Calculate the separation efficiency of the coalescer if the system should be design to separate oil droplets ($\rho_o = 800\ kg/m^3$) of diameter $D_o = 150\ \mu m$ with overall target efficiency $\eta_{tot} \geq 99.9\%$.
2. The engineer proposes an alternative configuration for the treatment plant in which the flotation chamber is shortened ($L' = 2\ m$) and a multi-plate coalescer $L_p = 10\ cm$ long is installed downstream the chamber. Water and oil droplets flow through the plates of the coalescer, δ away one from the other and slightly inclined upward; oil droplets accumulate on the plates, coalesce into larger droplets which can rapidly rise to the free surface. Calculate which should be the plate to plate distance δ to guarantee the same overall target separation efficiency for the alternative design.
3. Calculate the global separation efficiency of the alternative design configuration if the droplet size distribution is the one reported in Table.

D_o, $[\mu m]$	50	100	100
$m_o(D_p)$, $[mg]$	0.50	1.0	0.20

ee

In a fiberboard production plant, the burner used to produce the water vapor required for the process is fed using waste sawdusts derived from the same process. Flue gases ($Q = 3.5\ Nm^3/s$, normal condition 0^oC and $1\ atm$, $MM = 29\ kg/kmole$, $\mu = 1.8 \cdot 10^{-5} Pa \cdot s$) exiting from the burner at $T = 100^oC$ contain a large amount of dusts (dust concentration, $C_1 = 200\ mg/Nm^3$) which should be reduced to $C_2 = 10\ mg/Nm^3$ before emission from stack using a properly sized smoke treatment system. Since from flue gas sampling, the mean particle diameter of particles is $D_p = 20\ \mu m$, the engineer proposes to use a multistage smoke abatement system composed of a plate-plate ESP and a fabric filter, in series. Considering that the voltage available in the plant is $V = 60\ kV$ and the particle charge is $q_p = 5 \cdot 10^{-15} C$

1. Calculate the collection efficiency of the ESP, given ESP dimensions $W = 2\ m$, $H = 2\ m$ and $L = 5\ m$ if the ESP is made of 5 plates (2 high potential plates and 3 grounded);
2. Calculate which should be the efficiency of the fabric filter to achieve the target value of overall separation efficiency requested to the process.

ff

Flue gases of the same plant (ee) contain, together with particulate matters, Volatile Organic Compounds (VOC) originating from the resins used to produce the fiberboard panels. Flue gases should be cleaned before being released into the environment. An absorption column with internal packings is used for the purpose: gases are fed from the bottom of the column and water is fed from the top to promote transfer of VOC from the gaseous to the liquid phase.

1. Write a mass balance on the gas phase to describe mass transfer of VOC from the gas to the liquid;
2. Considering that column height and diameter are $H = 30\ m$ and $D = 3\ m$, that liquid flow rate is large enough to neglect VOC concentration in the liquid phase; that the mass transfer coefficient for VOC is $k = 7 \cdot 10^{-6} m/s$ and that the packing specific surface area is $a = 5000\ m^2/m^3$, calculate how much VOC is removed from the gas if the inlet concentration is $C_{in} = 10\ \mu g/m^3$.
3. Due to more stringent regulations for VOC concentration at stack outlet, the consultant suggest to revamp the absorption column changing the internal packing with a second generation type of packing ($a = 10000\ m^2/m^3$). Check if the revamping solution proposed allows to meet the new outlet concentration limit ($0.5\ \mu g/m^3$).

gg

In a surface finishing plant, the tanks used for the chemical treatment of metallic surface contains a basic solution of soda (NaOH 30% concentration) which reacts chemically with the metal producing an opaque surface. During this stage, microparticles of metal are released into the bath. The soda solution is continuously recirculated by a pump located at the end of the tank. To avoid clogging of the pump, the particle should settle down at the bottom of the tank before entering in the duct, feeding the recirculation pump.

1. Assuming that the typical size of particle released in the bath is $D_p = 10\ \mu m$, the density of particles is $\rho_p = 1500\ kg/m^3$ and the density and viscosity of the soda solution are $\rho = 1100\ kg/m^3$ and $\mu = 1.2 \cdot 10^{-3} Pa \cdot s$, and the tank is $L = 7\ m$ long, $W = 1\ m$ wide and $H = 1.6\ m$ high, calculate the maximum flow rate of the circulating solution which allows to settle down $\geq 90\%$ of the particles, preventing particle clogging;
2. a consultant claims that using a special flocculating agent, the sedimentation of the particles can be increased. In a laboratory test, particles sedimentation is achieved in 1/3 of the length of the tank. Calculate the average diameter of flocs formed by the flocculating agent.

hh

In a wastewater treatment plant, a bubble column is used to reduce the ammonia content of civil wastewaters (ammonia stripping by nitrogen). Small nitrogen bubbles ($\rho_G = 1.2\ kg/m^3$, $C_{NH_3}(0) = 0$) are injected at the bottom of a tank containing the wastewater ($\rho_L = 1000\ kg/m^3$, $\mu = 1 \cdot 10^{-3} Pa \cdot s$) up to $H = 3\ m$ level. The mass transfer of ammonia through the interface of bubbles from the liquid into the gas is promoted by the bubbles, rising by buoyancy and mixing wastewaters inside the tank. The gas bubbles escaping from the free surface of wastewater in the tank accumulate in the top volume of the tank and are exhausted using a fan.

1. Write a mass balance for the nitrogen rising bubble to describe mass transfer of ammonia from the liquid to the gas phase;
2. Assuming that the variation of ammonia concentration in the liquid phase is negligible ($C_{NH_3,int} = cost$) inside the tank, calculate which should be the bubble diameter to rise the ammonia concentration in the gas phase up to $0.5\ C_{NH_3,int}$ at the gas outlet (assume Stokes regime for the rising bubbles and mass transfer coefficient $k = 2 \cdot 10^{-8} m/s$).

jj

A chemical testing lab performs migration tests to evaluate the potential for contamination of solid waste (sands) to be used as filler in cement pastes. Pulverized material is loaded into a test column ($D = 10\ cm$, $H = 50\ cm$) and wetted with distilled water moving from the top to the bottom of the column and then recirculated back to the top for the 24 hours period test. The concentration of species migrating from the solid into the liquid is measured in the liquid phase at the end of the test period.

1. Write a mass balance for the liquid phase to describe the mass transfer of species from the solid (concentration of species at the liquid interface equal to $C_{int} = 5\ mg/L$) to the liquid phase;

2. Calculate the migration rate (mass transfer coefficient, k) for a species whose concentration in the liquid phase at the end of the test period is $5\ \mu g/L$ (water flow rate is $Q = 0.1\ L/s$, specific surface area for the packed column is $a = 100\ m^2/m^3$). Hint: consider the recirculating flow rate equivalent to a non recirculating flow rate moving along an very long packed column.

kk

In a livestock farm a stripping process is used to process agrifood wastewaters containing ammonia: ammonia rich filtered wastewaters ($\rho = 1000\ kg/m^3$, $\mu = 10^{-3} Pa \cdot s$) are fed into a sealed tank ($D = 2\ m$, height $H = 2\ m$) to be contacted with hot air bubbles ($\rho_b = 1.2\ kg/m^3$) injected from the bottom of the tank through ad hoc sized nozzles to promote the mass transfer of ammonia from the liquid to the gas, with a corresponding reduction of the ammonia content of the liquid waste.

1. Write a mass balance to describe the mass transfer of ammonia from the liquid to the gas assuming a negligible variation of ammonia concentration at the liquid/gas interface inside the tank ($C_{int} = 4\ mg/m^3$);

2. Considering a mass transfer coefficient $k = 1 \cdot 10^{-4} m/s$, calculate the variation of ammonia concentration in the gas as the bubbles rise through the wastewater. Express results as a function of bubble diameter.

3. Calculate ammonia concentration in the gas phase at the top of the tank if the bubble diameter is $d_b = 1\ mm$.

ll

A bubble column oxygenator ($D = 0.5\ m$, $L = 2\ m$) is used to abate odor emissions generated by a wastewater treatment plant. Wastewaters are fed from the top of the column ($Q = 3\ L/s$) and oxygen is injected from the bottom of the tank in the form of tiny bubbles. Oxygen contained inside the bubbles partially dissolves in the liquid while the bubbles rise along the column.

1. write a mass balance on the bubble oxygenator to describe the mass transfer of oxygen from the gas to the liquid phase; assume that the concentration of oxygen in the gas phase remains constant in time (C_{sat}), the mass transfer coefficient is given by $k = 1.6 \cdot 10^{-3} cm/s$ and the specific interfacial area is $a = 40\ m^2/m^3$).

2. Calculate the rate of oxygenation obtained for wastewaters;

3. Assuming that a depends on the oxygen mass flow rate and from the size of injected bubbles, discuss which are the best injection conditions to maximize the oxygen mass transfer to the liquid.

mm

In a sewage plant a biofilter ($L = 15\ m$, $W = 20\ m$, $H = 1\ m$) is used to abate the concentration of sulfuric odorous compounds: the gas to be treated is fed through the bottom where chemical compounds are adsorbed and degraded by the biomass ($C_{liq} = 0$) living in the liquid film adhering to the biofilter packing. Assuming that the specific interfacial area of the biofilter is $a = 50\ m^2/m^3$, the gas flow rate to be processed is $\dot{m} = 2.4\ kg/s$, gas density is $1.2\ kg/m^3$ and the mass transfer coefficient from the gas to the liquid is $k = 4 \cdot 10^{-3}\ m/h$:

1. Write a mass balance for the biofilter to describe the mass transfer of sulfur compounds from the gas to the liquid phase and calculate the biofilter abatement efficiency;

2. Calculate which should be the biofilter specific surface area to achieve 90% abatement efficiency.

nn

A chemical lab performs migration tests to evaluate the polluting potential of solid material extracted from quarries before it can be used as a filler. The test column ($D = 0.2\ m$, $L = 1\ m$) is loaded with pulverised rocks ($a_{int} = 10^4\ m^2/m^3$) and distilled water ($Q = 1\ L/s$) is fed from the top of the column to eluate the chemical species from the solid matrix into the liquid phase.

1. Write a mass balance to describe the mass transfer of chemical species from the solid to the liquid phase;

2. Assuming that the concentration of a chemical species is $C(L) = 300\ \mu g/L$, calculate which is the concentration of species in the solid phase if the mass mass transfer coefficient is $k = 10^{-6} m/s$.

3. Discuss how we should modify testing conditions to detect the concentration of chemical species present in traces (i.e. whose concentration is very small) in the solid matrix.

oo

A liquid scrubber has been designed to reduce H_2S emissions from a coal fired thermal power station located in Bulgaria. Water droplets ($D_p \simeq 200\ \mu m$) are sprayed inside the scrubber (a box with geometrical characteristics $H = 5\ m$, $W = 5\ m$ and $L = 10\ m$) through which the gas is flowing ($Q = 300,000\ Nm^3/h$). The gas pressure is atmospheric and temperature is 200^oC. Water droplets contain gypsum which can react with H_2S absorbed in the liquid phase to form salts ($C_{int,H_2S} = 0$).

1. Write a mass balance to describe the mass transfer of H_2S from the gas to the liquid phase (mass transfer coefficient is $k = 1.2 \cdot 10^{-4} m/s$, specific surface area is $a = 10^4\ m^2/m^3$);

2. Calculate H_2S abatement efficiency of the scrubber;

3. To comply with the more stringent regulations on emission limits, the scrubber abatement efficiency should increase further. A consultant suggests to reduce the size of water droplets sprayed inside the column to achieve a larger specific surface area; calculate how large should be a to achieve a target abatement efficiency $\eta = 95\%$;

4. The reduction of diameter for sprayed droplets increases the probability of liquid entrainment causing the transport of liquid droplets inside the stack ($H = 50\ m$, $D = 4\ m$); to collect entrained liquid droplets before the stack outlet, a spinner (fixed vanes centrifugal separator) has been installed at the base of the stack to impose a rotating velocity to the gas moving along the stack. Assuming that the rotation velocity of the fluid generates a constant radial acceleration acting on the water droplets, calculate how large should be the acceleration to collect 90% of the droplets (100 μm diameter, $\rho_d = 1000\ kg/m^3$) before the stack exit.

pp

Landfilling of wood based products containing heavy metals (Cu, As, Cr) may cause severe environmental impact. To limit the environmental pollution, a firm involved in waste disposal has developed a cost-effective treatment process to extract heavy metals from wood products. Wood is chipped in small pieces and loaded into a reactor (cross section $S = 2\ m^2$, height $H = 5\ m$). From the top of the reactor the chipped material (specific area $a = 4/d$ where d is the characteristic size of chips) is wetted by a sulfuric acid solution ($Q_L = 1.2 \cdot 10^{-3} m^3/s$); the solution enriched by eluated heavy metals is collected from the bottom of the reactor.

1. Write a mass balance for the washing fluid to describe the mass transfer of heavy metals from the solid (wood chips) to the liquid phase;

2. Assuming that the variation of concentration of heavy metals at the solid/liquid interface is $C_{int} = const$ and that the characteristic size of wood chips is $d = 8\ mm$, calculate the mass transfer coefficient for heavy metal migration if the concentration of heavy metals in the liquid at the bottom of the reactor is 0.9 C_{int};

3. Calculate which would be the concentration of heavy metals if the chip size is reduced to $d = 2\ mm$.

qq

An activated charcoal filter is used to reduce the concentration of odorous compounds from a process stream ($Q = 18000\ m^3/h$, $C = 20000\ OU/m^3$). The gas flow is fed to the filter (a porous sponge supported with charcoal particles) which is a box ($W = 3\ m$ wide, $H = 3\ m$ high and $L = 5\ m$ long) where the odorous compound is adsorbed on the filter surface ($k = 10^{-4} m/s$) and degraded. Assuming that the concentration of odorous compounds at the filter outlet should be $C_{out} = 200\ OU/m^3$,

1. calculate the filter abatement efficiency;

2. write a mass balance equation for the gas moving through the filter and calculate which should be the specific surface area of the sponge to achieve the target abatement efficiency;

3. Considering that the maximum pressure drop available to process the gas flow is $\Delta p = 5\ Pa$ and that the pressure drop through the filter can be calculated as $\Delta p = \mu K_H L V$ where V is the superficial flow velocity and $\mu = 1.8 \cdot 10^{-5} Pa \cdot s$ is air viscosity, evaluate which of the sponge types available from the market is the best suited.

	a, $[m^2/m^3]$	K_H	Cost/m^3
S1	5200	10^5	1500
S2	10400	$1.8 \cdot 10^5$	230

rr

A packed column filled with a solid reactants (A) is used to prepare the solution to be fed to a laboratory reactor. For the economical viability of the reaction process, the solid reactant should be dissolved into a liquid phase (flow rate $Q = 0.5\ L/s$) whose initial concentration of A is zero reaching a concentration $C = 0.7\ C_{sat}$ before entering in the laboratory reactor.

1. Write a mass balance to describe the mass transfer of solid reactant to the liquid phase;
2. Assuming $a_{int} = 10^4\ m^2/m^3$ and $k = 10^{-6} m/s$, calculate how long should be the column if $D = 0.2\ m$;
3. Discuss how the column design should be changed to minimize its envelope.

tt

The dryer used to reduce the moisture content of food powders is made of a pipe in which hot dry air transports in suspended mode the particles to be dried.

1. Given the air flow rate, Q, the particle characteristics (diameter D_p, density ρ_p, moisture fraction at inlet, $X_{p,0}$, [kg water/kg solid]), write a mass balance to describe the variation of moisture fraction for the particles (assume that the mass transfer rate for water from the particle to the gas is known and that this transfer does not change significantly the moisture fraction of the gas phase, X_g);
2. calculate the variation of X_p along the dryer;
3. Discuss which are the relevant variables (device characteristics, operating conditions) which can be modified to achieve the maximum reduction of the moisture content at the outlet of the dryer.

uu

In an anodic oxidation plant a scrubber is used to wash the vapors containing H_2SO_4 exhausted from the area surrounding the process pools. Flue gases fed from the bottom of the column rise exchanging mass countercurrently with liquid droplets (water + $NaOH$) injected from the top of the column and falling down driven by gravity. Due to $NaOH$, once in the liquid phase H_2SO_4 reacts forming salts.

1. Write a mass balance for the gas phase to describe the mass transfer of H_2SO_4 from the gas to the liquid phase (droplets, $D_p = 100\ \mu m$, liquid fraction $\epsilon = 0.3$ in the control volume); assuming that the mass transfer coefficient can be written as $K = k_0/D_p$ where $k_0 = 3.6 \cdot 10^{-10}$ and K in [m/s], calculate how long should be the scrubber to achieve 95% abatement efficiency for the acid if the gas flow rate is $Q_G = 10000\ m^3/h$ and the column diameter is 4 m;
2. To reduce the volume of the scrubber is possible to (i) increase the amount of liquid to be atomized (doubling the liquid volume fraction in the scrubber), or (ii) atomize the same amount of liquid into smaller droplets. Discuss on the pros and cons of these two alternatives.

vv

In an industrial plant, an absorption column is used to wash the vapors containing H_2SO_4 released by the anodic oxidation process. H_2SO_4 is absorbed by a water solution of $NaOH$ which falls down along the internal packing of the column. $NaOH$ reacts with H_2SO_4 forming Na_2SO_4 which precipitates as salt in the liquid solution. The flow rate of flue gases is $Q = 7\ m^3/s$, H_2SO_4 concentration of gas at column inlet is $C_0 = 500\ mg/m^3$. The mass transfer coefficient, measured by experiments, is $k = 6 \cdot 10^{-3} m/s$.

1. Write a mass balance for the gas phase to describe the mass transfer of H_2SO_4 from the gas to the liquid phase;
2. Given a packed bed porosity $\epsilon = 0.6$, a packed bed thickness $H = 2.5\ m$ and the characteristic size of packing $d = 1\ cm$, calculate which is the concentration of H_2SO_4 in the gas phase at the column outlet;
3. The local environmental agency fixed a limit for H_2SO_4 concentration at stack outlet equal to 5 mg/m^3. Calculate which should be the value of the abatement efficiency;
4. How should we change the column configuration to achieve the target abatement efficiency?