Homework N° 1: storage/transport of incompressible fluids

a.

An absorbing tower is used to abate the concentration of pollutants contained in the flue gases emitted by an industrial plant. The height of the tower is 20 m. The washing fluid (water, flow rate $Q = 20 \ l/s$, density $\rho = 10^3 kg/m^3$, viscosity $\mu = 10^{-3} Pa \cdot s$), is pumped up to the top of the tower using a pipe and then atomized in droplets inside the tower; droplets fall down by gravity while the gas is rising through the tower, absorbing the gaseous pollutants. Calculate:

1. the pumping power necessary to deliver the fluid up to the top of the tower if the pipe is smooth and its diameter is $D = 0.1 \ m$ (use Blasius equation to compute the friction factor);

2. the pumping power necessary to deliver the fluid up to the top of the tower if the pipe is rough (surface roughness $k = 1 \ mm$) (use Colebroke equation to compute the friction factor).

b.

Flue gases emitted from the stack of a thermal power plant, rich of water vapour, may condensate by rapid cooling once released in the atmosphere, leading to acid rain out nearby the plant. To avoid acid rain out, the chimney is equipped with a condensate extraction system: gutters installed inside the chimney are used to collect and extract the vapour condensing as a liquid film at the inner wall. The chimney height is $80 \ m$, the diameter is $D = 8 \ m$, the condensation rate is $\dot{q} = 0.01 \ kg/m^2 s$ and gutters interdistance along the stack is 4 m; calculate the diameter of draining pipes which allow to dispose the condensate by gravity at the bottom of the stack.

c.

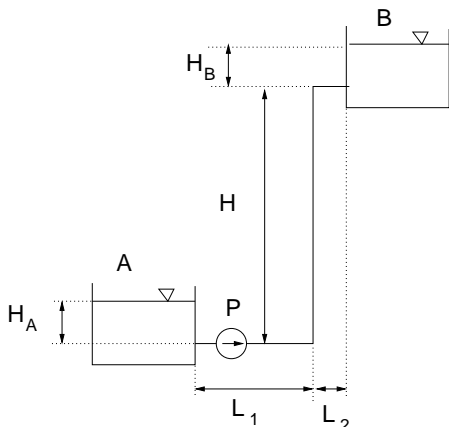Figure 1 shows the sketch of a fire-fighting system installed in a chemical plant.

The system is made of two tanks, one (tank A) at groud level and one elevated (B). Tank A is used to fill periodically tank B. Pressurized water can be discharged from tank B when required for fire-fighting purposes. Given $H_A = 1 \ m$, $H = 60 \ m$, $L_1 = 30 \ m$, $L_2 = 50 \ m$ e $D = 0.1 \ m$, calculate the pumping power to fill tank B in 2 hours (volume $V_B = 32 \ m^3$).

d.

A pipeline should be designed to transport fluid from tank A to tank B (as shown in Figure 2) as economically as possible. The pipe is smooth and:

- the cost of the pipe is $1.8 \cdot 10^3 \ D = k_t D$ euro/m, where D is the pipe diameter in meters;

- the cost of the pumping station is $3.5 \cdot 10^3 = k_p$ euro/kW installed;

- operating costs are $0.150 = k_e$ euro/kWh;

- expected life time for the plant is $N_y = 20 \ years$ and plant design operating hours are $N_h = 5000 \ hours/year$.

Calculate:

1. the economically optimum diameter of the pipeline to deliver a water flow rate equal to 2.0 m^3/s (assume that the branch of the pipeline not including the pump is closed by the valve).

2. for that diameter, or the nearest diameter commercially available, calculate the power of the pump.

3. calculate the economically optimum diameter of the pipeline is the flow rate to be transferred from A to B is 2.0 m^3/s and water can flow also in the brach without the pump.

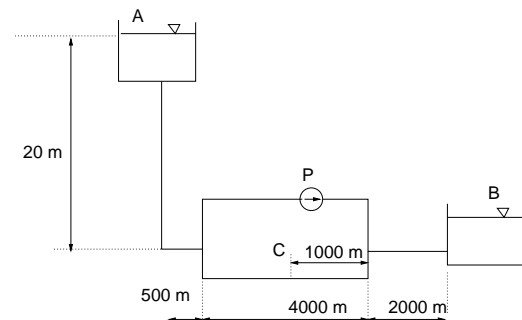Figura 1. Sketch of tanks serving a fire-fighting system.

Figura 2. Sketch of transport pipeline.

e.

Oil ($\rho_{oil} = 800 kg/m^3$ and $\mu_{oil} = 1.2 \cdot 10^{-2} Pa \cdot s$, mass flow rate $W = 1500 \ kg/s$) is transported through a pipeline from storage tank A to a point B, 8 km apart over a hill (height 50 m). The maximum height if the hill is 5 km far from A. The pipeline diameter is $d = 1.25 \ m$, and pipe surface roughness is $\epsilon = k/D = 0.001$. Calculate the pumping power to transport the oil considering that the vapour pressure of oil at reference environmental conditions is $P_v = 2.4 \ kPa$.

f.

The hydraulic line shown in Figure 2, with recirculating loop in the horizontal plane, is made of smooth pipes (diameter $D = 0.15 \ m$). The loop is used to deliver $w_0 = 20 \ kg/s$ of water to tank B. Neglecting the pressure drop along the vertical branch (shorter than the horizontal parts)

1. calculate the pumping power required to deliver the flow;

2. if a leakage of fluid is produced at point C (leakage area 0.5 cm^2), calculate the flow rate delivered to tank B in this case.

g.

In the flow loop shown in Figure 3 the pump P delivers a flow rate equal to 28 kg/s of oil ($\rho = 820 \ kg/m^3$, $\mu = 5. \cdot 10^{-3} Pa \cdot s$). The pipe is smooth and the diameter is 0.12 m. Calculate

1. the pumping power if the valve V is closed.

2. the flow rate delivered from one tank to the other if the valve is partially open and generates pressure drop corresponding to equivalent pipe lengths equal to a) 1000 m, end b) 100 m, respectively.
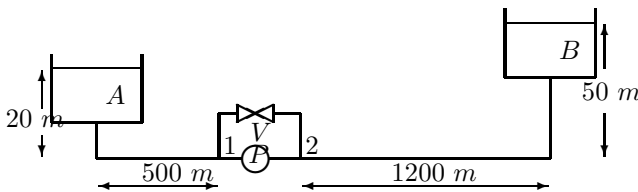

Figura 3. Flow loop for fluid transfer between two tanks.

h.

A flow rate $\dot{m} = 50 \ kg/s$ of fluid ($\rho = 880 \ kg/m^3$, $\mu = 1. \cdot 10^{-3} Pa \cdot s$) is transferred from tank A to tanks B and C in equal amounts, as shown in Figure 4. Pipelines are horizontal, tank C is 30 m high and tank B is 40 m high; calculate:

1. the minimum pumping power required to transfer the fluid if pipe diameters are 0.18 m in all branches

of the loop (pipes are smooth, one of the valves is fully open and one partially open as required to transfer the same flow to B and C).

2. the economically optimum diameter of the pipelines if branch a can be different from branch b and c; the cost of the pipe is $1.2 \cdot 10^3 \cdot D = k_t D$ euro/m, the cost of the pumping station is $k_p = 2 \cdot 10^3$ euro/kW installed and operating costs are $k_e = 0.150$ euro/kWh. Assume that the life time of the plant is equal to $N_y = 12$ years and $N_h = 5000$ working hours/year.
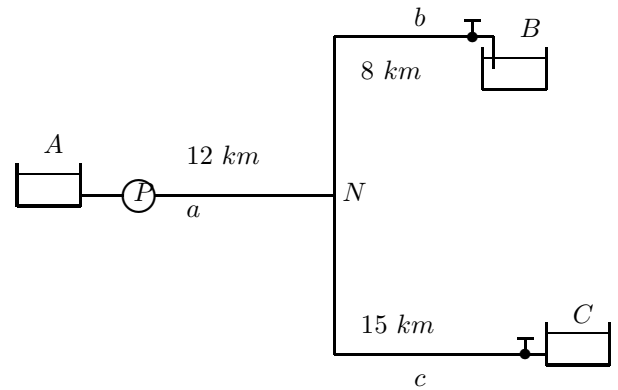

Figura 4. Sketch of hydraulic line used to deliver the same amount of flow to tank B and C.

i.

The cooling system of an industrial plant, sketched in Figure 5, use a pressurized tank A to pump water to different utilities (points B and C) inside the plant.

1. Calculate the pressure of gas in tank A to deliver a mass flow rate $w_B = 9.5 \ kg/s$ to tank B if valve V is closed.

2. Calculate the pressure of gas in tank A to deliver a mass flow rate $w_B = 9.5 \ kg/s$ to tank B when valve V is open and a mass flow rate equal to $w_C = 8 \ kg/s$ is delivered to C. Calculate the pipe diameter in branch N-C.

Assume smooth pipes ($f = 0.079 \cdot Re^{-0.25}$) and the following numerical values: $h_A = 1 \ m$, $h_C = 2 \ m$, $D_{AB} = 0.1 \ m$, $L_1 = 40 \ m$, $L_2 = 160 \ m$.
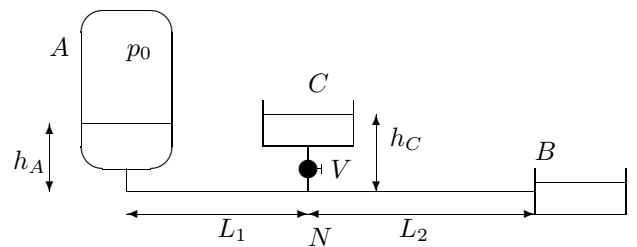
Figura 5. Sketch of cooling plant.

j.

A cylindrical tank ($D = 20\ m$) storing oil (density $\rho = 800\ kg/m^3$) is equipped with an overflow discharging valve of diameter d located at $\overline{h} = 20\ m$ above ground and is fed by a constant flow rate $Q_0 = 0.5\ m^3/s$. The starting level of oil is $h_0 = 1\ m$. Calculate:

1. the time after which the overflow discharging valve starts working;

2. the maximum level reached by the oil as a function of overflow discharging valve diameter d (unknown);

3. the value of d to contain within an external cylindrical basin (diameter $D_m = 40\ m$) the jet of water exiting from the valve; the time to reach the alarm level of oil in the tank $h^* = 21\ m$.

k.

A sealed tank (height $H = 10\ m$, diameter $D = 10\ m$) contains oil ($\rho = 800\ kg/m^3$, $\mu = 0.5\ Pa{\cdot}s$) up to $h = 6\ m$ and air ($M = 29$, $R = 8314$) at atmospheric pressure. The tank is connected by a valve V to a smooth pipe ($d = 0.1\ m$, length $L = 10\ m$). When the valve V is opened, oil starts flowing along the pipe. Assuming isothermal conditions in the tank, ($T = 20^o C$),

1. calculate the final level of oil in the sealed tank.

2. write the equations controlling the emptying of the oil tank and calculate (if possible) how long it takes for the oil to reach the final level.
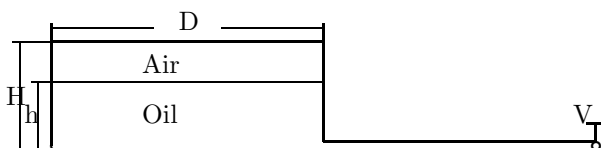
Figura 6. Oil flux exiting from a sealed tank.

l.

Consider a continuous feed tank reactor operating at steady state conditions (volume V, inlet/outlet flow rate Q). At time $t = 0$ the inlet stream concentration increases steeply from 0 to $C_{A,0}$ and $C_{B,0}$.

1. calculate the evolution of concentration for species A and B at the outlet of the tank if the system is perfectly mixed;

2. calculate concentration evolution for species A and B if species A reacts inside the tank to form species B and reaction rate $r_B = K_{react}C_A$.