Water reuse: calculating energy demand in membrane technology

Answers to questions

Question 1:

Which of these two options − municipal water reuse or seawater desalination − would you imagine is the least expensive to run and why?

Answer:

At this stage, it's not possible to say which of the two options incurs the greatest cost. However, it's reasonable to assume in both cases that energy consumption is a significant contributor.

The main contributors to water and wastewater process operating expenditure (or OPEX) generally are: energy and chemicals consumption, component replacement (including membranes, as well as hardware such as valves and pumps), waste disposal and labour.

Question 2:

What are the units of flow x pressure? Which of the derived SI units do these units relate to?

Answer:

Flow has units of m^3/s; pressure has units of $kg/(ms^2)$.

So, flow x pressure takes units of $kg\ m^3 / (s.m.s^2)$, or $kg\ m^2/s^3$. These are the same units as for power.

Question 3:

What are the units of power/mass flow? What are the units of energy/mass? What are the units of this parameter when multiplied by the density (which has units of kg/m^3)?

Answer:

The units of power are $kg\ m^2/s^3$. Mass flow has units of kg/s. So power per mass flow has units of m^2/s^2.

The units of energy are kg m^2/s^2. So, energy per unit mass has the same units as power per unit mass flow (i.e. m^2/s^2).

If this is multiplied by density, which has units of kg/m^3, then it becomes kg/m^3 x m^2/s^2 = $kg/(m\ s^2)$. These are the same units as those of pressure.

Question 4:

Referring back to the equations you saw in Section 2, how much power in kW does it take to pump 1,000 m^3/h of water at 0.5 bar pressure?

Answer:

Power = flow x pressure.

In SI units: 1 bar is 10^5 Pa or 100 kPa, so 0.5 bar pressure is 50 kPa; 1000 m^3/h is 0.278 m^3/s.

So, the power is 50 x 0.278 = 13.9 kW.

Question 5:

How much power is required to produce the above product flow if it represents only half of the feed flow, and the feed flow has to be pumped to 54 bar?

Answer:

Feed flow rate = 2 x product flow rate = 2 x 0.278 = 0.556 m^3/s.

Pressure = 54 bar = 5400 kPa.

So, the power required to generate the product is 0.556 x 5400 kPa = 3002 kW (or 3 Mega Watts, MW).

Question 6:

What is the specific energy consumption (SEC) in kWh per m^3 product for the above?

Answer:

This power generates 2000 m^3/h product flow.

Specific energy consumption (SEC, kWh/m^3) = Power (kW) / Flow (m^3/h).

So, SEC = 3000 kW / 2000 m^3/h = 1.5 kWh/m^3.

Question 7:

Using the above equations, calculate the flux, in both LMH and SI units, for a permeate flow of 150 m^3/hr through 200 membrane modules each having an area of 30 m^2.

Answer:

Flux J = Flow/Area, where the flow is in litres per hour and the area is provided by 200 modules at 30 m^2.

So, J = 1000 x 150 / (200 x 30) = 25 LMH.

In SI units of $m^3/(m^3.s)$ the flux would be 25 / (200 x 30 x 3600) = 1.16×10^{-6} m/s.

Note that flux has units of velocity (and in some old text books is referred to as 'filtration velocity').

Question 8:

If the permeability is 80 LMH/bar, what is the TMP?

Answer:

Permeability (LMH/bar) = Flux/TMP, for flux in LMH and TMP in bar.

So TMP = Flux/permeability = 25/80 = 0.313 bar.

Question 9:

If the feed flow is 43 L/s, what is the recovery?

Answer:

Converting flow to m^3/h: Q = 43 L/s x 3600 (s/h) / 1000 (L/m^3) = 155 m^3/h.

So, recovery = permeate flow/feed flow = 150/155 = 96.9%

Question 10:

Calculate the specific aeration demand in

(i) Nm^3/h per m^2 membrane area, and
(ii) Nm^3 per m^3 permeate, if air is delivered to these 200 modules at a rate of 2400 Nm^3/h.

SAD_m = Aeration rate/area = 2400/(200 x 30) = 0.40 Nm^3/h per m^2.

Answer:

(a) Specific aeration demand with reference to membrane area SAD_m = Aeration rate / membrane area, where membrane area = 200 modules x 30 m^2/module = 6000 m^2.

So, SAD_m = 2400 Nm^3/h / 6000 m^2 = 0.40 Nm^3/h per m^2.

(b) Specific aeration demand with reference to permeate volume $Q'_{a,m}$ = SAD_m / flux, for flux in units of $m^3/(m^2h)$.

A flux of 25 $L/(m^2h)$ is 0.025 $m^3/(m^2h)$, so $Q'_{a,m}$= 0.40 / 0.025 = 16 Nm^3/m^3 permeate.

Question 11:

Where is energy used in this flowsheet? [*HINT:* there are five places in total]

Answer:

Membrane aeration, biological aeration, sludge transfer, permeation and agitation.

Question 12:

Based on the calculated data from Section 4, determine the SEC for the membrane air scour.

Answer:

SEC for membrane air scour $E_{a,m} = E'_{a,m} Q'_{am}$

$E'_{a,m} = 0.011/\varepsilon$ kWh/Nm^3 air, where ε is the pumping efficiency, assumed to be 60%.
According to Question 10(ii), $Q'_{a,m}$= 16.

So, $E_{a,m}$ = (0.011 / 0.6) x 16 = 0.293 kWh/m^3 permeate.

Question 13:

Calculate the oxygen demand and so the specific aeration demand ($Q'_{a,b}$) and then the SEC for the process tank aeration.

Answer:

SEC for biological aeration $E_{a,b} = E'_{a,b} Q'_{a,b}$.

$Q'_{a,b} = 0.023\ O_2$ Nm^3 air per m^3 permeate; $E'_{a,b} = 0.013/\varepsilon$ kWh per Nm^3 air; $O_2 = 0.67 \times$ COD; ε is the pump efficiency as before, assumed to be 60%.

So, for COD = 800 mg/L, $E_{a,b} = 0.67 \times 800 \times 0.013 \times 0.023 / 0.6 = 0.271$ kWh per m^3 permeate.

Question 14:

Calculate the energy for pumping and stirring the sludge, and for pumping the permeate through the membrane.

Answer:

(a) Sludge pumping and stirring energy $E_s = 0.032 / \varepsilon$, where $\varepsilon = 60\%$ as before.

So, $E_s = 0.032 / 0.6 = 0.053$ kWh/m^3 permeate.

(b) Permeate pumping energy $E_p = (P + P_{loss,filt})/(36\ \varepsilon)$, where P is the transmembrane pressure, calculated in Question 8, and $P_{loss,filt}$ the pressure losses, assumed to be 0.15.

So, $E_p = (0.15 + 0.313)/(36 \times 0.6) = 0.021$ kWh/m^3 permeate.

Question 15:

Determine the total SEC for the MBR, based on the feed flow (NB: the feed flow is the retentate flow/recovery).

Answer:

The total energy must be divided by the conversion, calculated from Question 9 to be 96.9%.

So, the total SEC of the MBR, $E_{MBR} = (E_{a,m} + E_{a,b} + E_s + E_p + E_{pi}) / R = (0.293 + 0.271 + 0.053 + 0.021 + 0.10)/96.9\% = 0.76$ kWh/m^3 permeate.

The aeration components ($E_{a,m}$ + $E_{a,b}$) / R make up around 76% of the total SEC.

Question 16:

Seawater typically has a concentration of around 3.5%. What is the optimum CF at this concentration, and what is the resultant SEC?

Answer:

The spreadsheet should be used to determine the impact on the SEC of incrementally increasing the CF value. Accordingly, a minimum in the SEC can be determined at a CF of ~1.8. Note that recovery R = 1 - 1/CF = 44%.

Question 17:

The wastewater has a dissolved solids concentration of 1000 mg/L. What is this in wt%, and how does the SEC change with CF at this concentration? What does this imply about the energy recovery turbine?

Answer:

Concentration = 1000 mg/L = 1 g/L = 0.1 g per 100 mL, which is ~ 0.1 g per 100g, and so 0.1 wt%.

(a) Using the spreadsheet in the same way as in Question 16, the optimum CF is ~3.5 when SEC = 0.74. So, the recovery is much higher than for RO - around 71% cf. 44%.

(b) Given the probable cost of the energy recovery turbine, investing in it is unlikely to be justified to recover a fraction of a kWh/m^3. You can check the loss of recovered energy from removing the energy recovery turbine by entering a value of 0% in the turbine efficiency value and noting the change in SEC.

Question 18:

Pre-treatment is by membrane filtration, similar to the membrane filtration component of the MBR where the energy consumption is from permeate pumping. What is the approximate SEC for this step?

Answer:

Assuming the SEC for the UF/MF membrane pre-treatment to be the same as the permeate pumping component of the MBR (from Question 14(b)), then E_p = 0.021 kWh/m^3 for the

MBR filtration.

According to the RO calculation from Question 16, only 44% of the UF/MF filtrate is converted to product. So, E_p = 0.021/0.44 = 0.048 kWh/m^3 overall.

Question 19:

What is the optimal total SEC for the RO desalination route?

Answer:

The SEC for the RO step, according to Answer 16, is 4.17 kWh/m^3. The UF/MF pre-treatment, according to Answer 18, has a SEC of 0.048 kWh/m^3.

So, the total SEC for RO is 4.17 + 0.048 = 4.22 kWh/m^3.

Question 20:

What is the optimal total SEC for the MBR wastewater recycle route?

Answer:

For the MBR, as with the UF/MF pre-treatment step in Answer 17a, around 71% of the MBR permeate can be assumed to form the RO permeate product. So, the SEC for the MBR step = 0.76 kWh/m^3 (according to Answer 15) / 0.71 = 1.07. For the RO downstream of the MBR the SEC is 0.74, also from Answer 17a.

So, the total SEC for the MBR and the RO post-treatment = 1.07 + 0.74 = 1.81 kWh/m^3.

Question 21:

What do you conclude from your analysis? Which of the two options − municipal water reuse or seawater desalination − is the most cost effective in terms of energy?

Answer:

Wastewater recycling incurs less than half the energy of seawater desalination. So, based on energy efficiency alone, wastewater reuse would always be the preferred choice of water supply.